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16. Abstract

This document discusses three criteria currently under consideration for operating independent approaches to converging runways under Instrument Flight Rules. These criteria include the Worst-Case Boundaries, developed for the Federal Aviation Administration (FAA) by The MITRE Corporation; the application of nonoverlapping Terminal Instrument Procedures (TERPS) obstacle clearance surfaces to provide protected airspace, developed by the FAA's Air Traffic Operations Service; and Tower-Applied Visual Separation on Missed Approach, currently used in Chicago.

A Single Criterion is then proposed which combines elements of the TERPS Criterion and the Worst-Case analysis. This criterion provides explicit blunder protection and its dimensions are functions of measurable navigation performance parameters. However, the decision heights obtained using the Single Criterion are generally higher than those obtained using the TERPS+3 Criterion. This leads to the conclusion that, using the techniques described for the Single Criterion, decision heights lower than those generated by the TERPS+3 Criterion may not be feasible for independent IFR approaches to converging runways. However, the Single Criterion may be useful in the future because it is directly related to aircraft performance on missed approach. Any improvements in navigation and/or aircraft performance can be reflected in this criterion, with a corresponding lowering of decision heights.

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EXECUTIVE SUMMARY

INTRODUCTION

Congestion at major airports has prompted the development of several concepts for increasing airport and airspace capacity. One of these concepts is the operation of independent precision approaches to converging runways under Instrument Flight Rules (IFR). For the purpose of this analysis, converging runways are defined as runways with an included angle between 15 and 100 degrees. (These runways may intersect if the distance from each threshold to the intersection point is at least 8400 feet.) The purpose of this report is to describe three criteria defining IFR approaches to converging runways that are currently under consideration, and to propose a single criterion that would be acceptable to the aviation community.

Although approaches to converging runways are currently allowed under Visual Flight Rules (VFR), they are not permitted under IFR. This is because straight missed approach paths for the two runways would intersect, and simultaneous missed approaches, though an extremely rare occurrence, are possible. Thus, although the arriving aircraft are separated on approach, if both were to execute straight missed approaches, a conflict between them could result. This possibility must be incorporated into tne airspace design for each approach by providing airspace for turning missed approaches. Thus, the primary objective of this analysis of IFR approaches to converging runways is to provide an adequate volume of protected airspace for aircraft executing simultaneous missed approaches. The other objective is to develop a criterion that accounts for a severe navigation error (blunder on missed approach).

CRITERIA FOR IFR APPROACHES TO CONVERGING RUNWAYS

Several criteria have been proposed for operating independent IFR approaches to converging runways. The following sections describe each of these criteria.

Worst-Case Boundaries Criterion

The concept of converging approaches was studied by The MITRE Corporation in 1981. This study recommended both a volume of protected airspace and explicit protection against a blundering aircraft, where a blunder is defined as the failure of an aircraft to follow the turning missed approach procedures. (That is, the aircraft flies a straight missed approach, rather than turning.) A "Worst Case" was assumed, and boundaries were assigned to protect aircraft in the event of its occurrence. The elements of the Worst-Case Boundaries, shown in Figure A, are the following:

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Boundary Dimensions (200-ft. Decision Height)

— 1.5 nmi Straight Segment
— 211 ft. from Flight Path to Boundary at MAP
— 943 ft. from Flight Path to Boundary at Turning Point
   (3.5 Degree Divergence Angle)
— 1.75 nmi Turning Boundary Radius
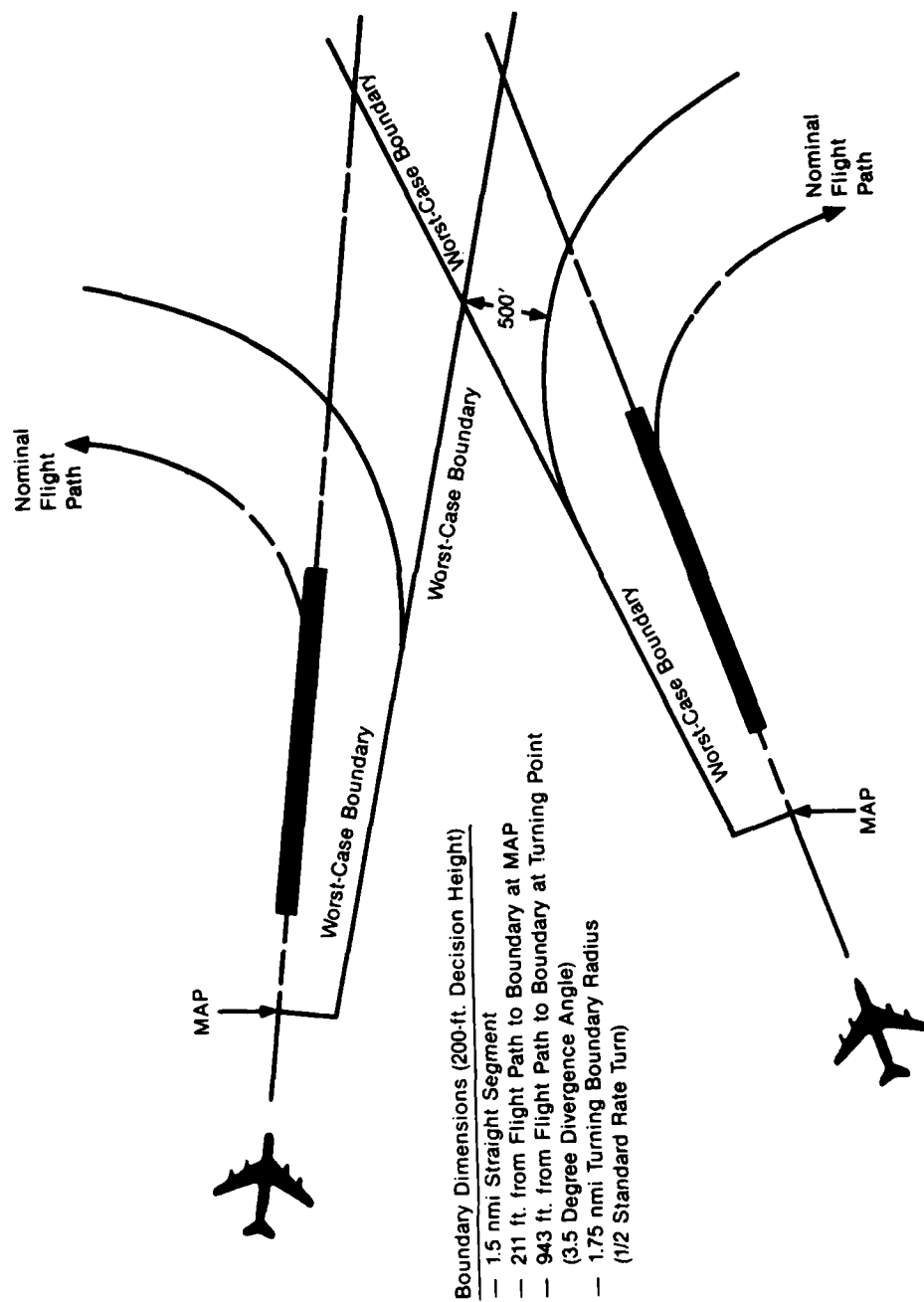   (1/2 Standard Rate Turn)

FIGURE A
WORST-CASE BOUNDARIES

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1. It is assumed that aircraft fly straight ahead for 1.5 nautical miles (nmi) before turning to stabilize the aircraft and gain altitude. This straight segment is protected by a straight boundary that is at least three standard deviations (of the applicable statistical distribution) away from the nominal flight path.

2. At the end of the straight segment, the aircraft is assumed to turn at standard rate. The turning segment is protected by a turning boundary (curving away from the opposite approach) that is a continuation of the straight boundary. This turning boundary has a radius of 1.75 nmi, corresponding to a half-standard-rate turn for a Category D aircraft.

3. The straight boundary is extended beyond its intersection with the turning boundary. This extension is assumed to be the path of the blundering aircraft. This extension must be separated from the opposite boundary by a distance of at least 500 feet.

Thus this analysis provides both a volume of protected airspace (enclosed by the straight and turning boundaries) and an explicit provision for protection against one aircraft failing to turn according to the missed approach procedures.

TERPS+3 Criterion

The TERPS+3 Criterion was proposed by the Industry Task Force on Airport Capacity Improvement and Delay Reduction and developed by FAA's Air Traffic Operations Service. This criterion, shown in Figure B, applies Terminal Instrument Procedures (TERPS) obstacle clearance surfaces for turning missed approaches (of 90 degrees or greater) to converging runways as a means of providing protected airspace. These surfaces for each missed approach must not overlap, and the Missed Approach Points (MAPs) for the two approaches must be separated by at least 3 nmi. (If necessary, to satisfy both the nonoverlapping TERPS and 3-nmi separation requirements, the MAPs are relocated farther back on the approaches.) It should be noted that this criterion does not explicitly protect against a blundering aircraft and provides no horizontal separation between the surface boundaries.

Tower-Applied Visual Separation During Missed Approach

Approaches to converging runways have been operated at Chicago's O'Hare International Airport for approximately 15 years using the procedures shown in Figure C. These procedures define one

Boundary Dimensions (200-ft. Decision Height)

— 1.5 nmi Straight Segment
— 1,042 ft. from Flight Path to Boundary at MAP
— 3,038 ft. from Flight Path to Boundary at Turning Point
  (12.4 Degree Divergence Angle)
— 3.5 nmi Turning Boundary Radius
  (1/4 Standard Rate Turn)

Nominal Flight Path

MAP

3 nmi
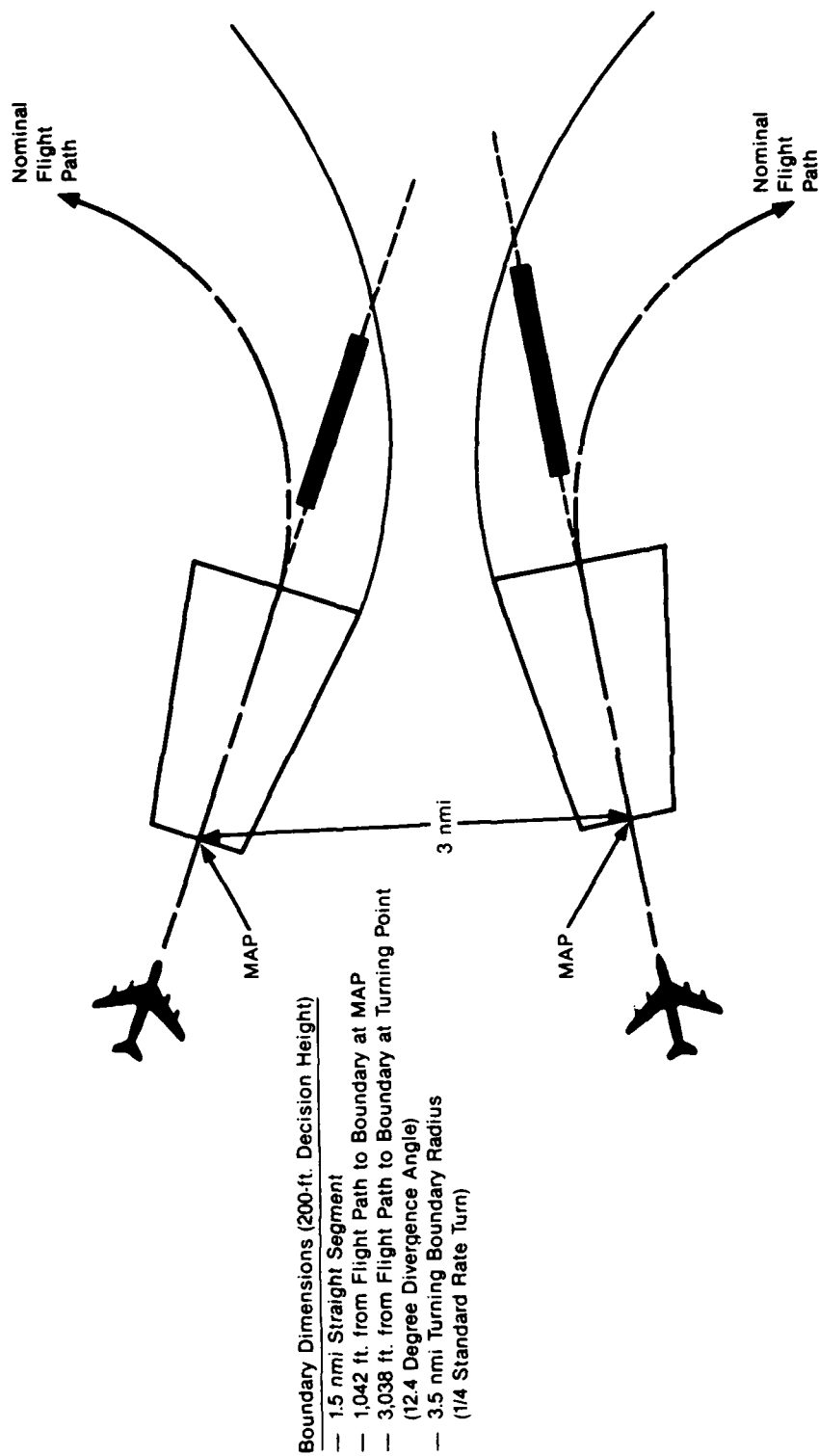
FIGURE B
TERPS+3 BOUNDARIES

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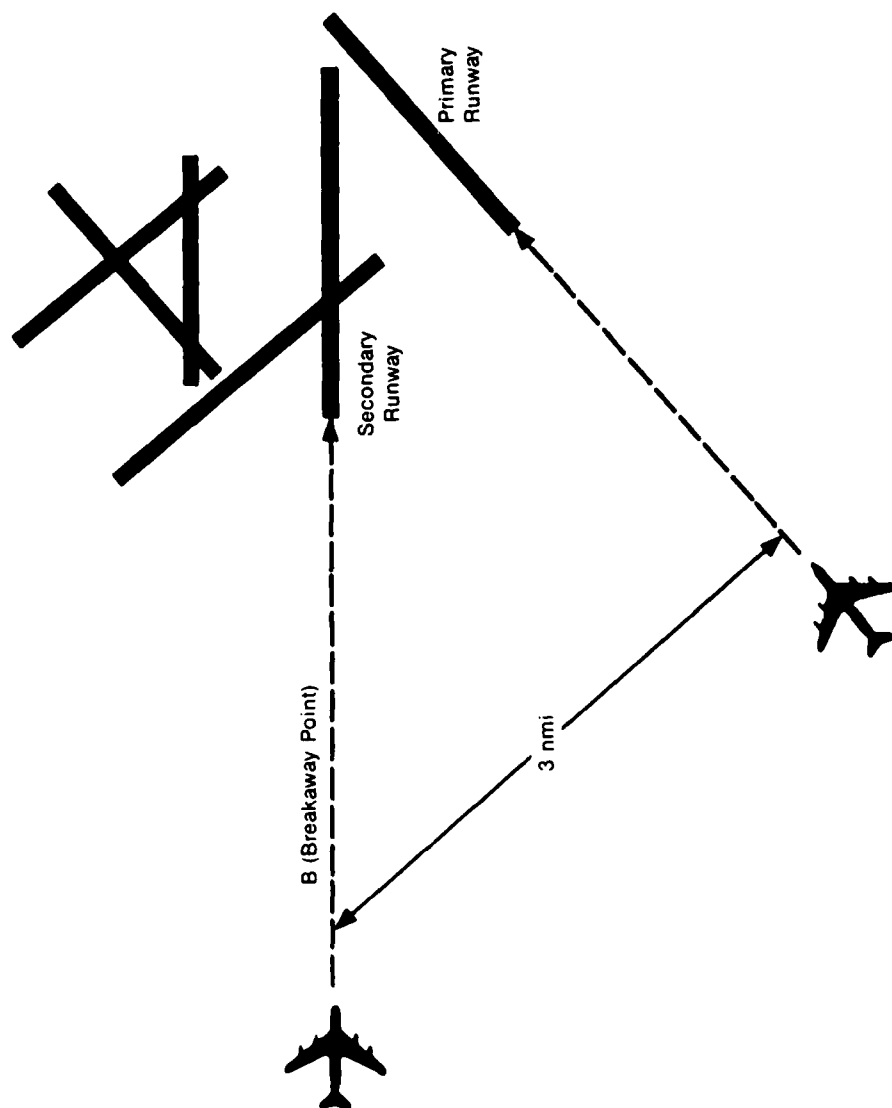
FIGURE C
TOWER-APPLIED VISUAL SEPARATIONS

Primary Runway

Secondary Runway

B (Breakaway Point)

3 nmi

runway as "primary" and the other a "secondary". Aircraft on the primary runway use the standard Decision Height (DH) for that approach, and are cleared to land independently from operations on the secondary runway. A "breakaway point" is defined on the secondary approach; it is the point where the secondary aircraft first comes within 3 nmi of the primary runway's localizer course. Aircraft on the secondary approach are cleared to land if, at the breakaway point, the pilot reports "runway in sight" and "landing assured" or if the tower controller has the aircraft in sight. If neither of these conditions is met, the tower controller issues a go-around order to the aircraft on the secondary approach.

Need for a Single Criterion

Although each of the proposed criteria can be (or has been) implemented, there are difficulties associated with using each of them for IFR approaches under Instrument Meteorological Conditions (IMC). Because many flight operations experts are intuitively uncomfortable with the size of the Worst-Case Boundaries, they have not been accepted by the aviation community. The TERPS+3 Criterion is based on the avoidance of stationary obstacles below the surfaces rather than other aircraft, which are above the surfaces. Finally, the Tower-Applied Visual Separations are based on visual separation during missed approaches.

MISSED APPROACH DATA AND RISK ASSESSMENT

The TERPS and Worst-Case criteria described above are based on analyses of the risk of flying a missed approach. These analyses were performed using the available missed approach data, which came from the following sources:

1. Missed Approach Flight Simulation Study -- this study, sponsored by the FAA, consisted of approximately 120 missed approaches flown by airline pilots on flight simulators for aircraft ranging from Cessna Citations to Boeing 747s. In addition, 15 actual missed approaches were flown with an FAA B727 aircraft to verify the results of the simulation. (1975-1976).

2. Project Lookout -- this FAA study consisted of 179 missed approaches flown by piston-engined and jet aircraft in 1965.

3. United Kingdom Certification Data -- this consisted of 168 missed approaches flown to a nominal DH of 100 feet.

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There are many problems associated with the data. Very few data exist, and all of them are for straight missed approaches only. In addition, the data were recorded only a limited distance (up to 8800 feet) downrange from the MAP.

Previous Studies Using Missed Approach Data

Several earlier studies have used missed approach data for various purposes. The use of the existing data by these studies shows several methods of protected airspace design and risk assessment.

The Worst-Case Boundaries analysis combined the Flight Simulation and Project Lookout data to produce descriptive statistics on the distribution of lateral deviation about the nominal flight path on missed approach. A boundary three standard deviations from the nominal flight path along the straight segment of the missed approach was then produced from these statistics. This analysis also included a turning boundary and a provision for blundering aircraft.

Missed approach data were also used in the design of TERPS obstacle clearance surfaces. The design of these surfaces was based on aircraft performance characteristics, estimation (based on the experience of the analysts), and analysis of data generated by flight tests. Although there were not enough observations to constitute a statistically valid data base, the analysts "looked at" the data on aircraft dispersion on missed approaches to help determine the size of the surfaces.

Vertical and lateral distributions of aircraft on missed approach were used in the development of the International Civil Aviation Organization's Collision Risk Model (CRM). The vertical distributions describe aircraft performance during the initial phase of a missed approach. The lateral distributions are based directly on data. These distributions are combined to form the missed approach section of the model, which generates a numerical estimate of the risk of collision between an aircraft and an obstacle for a specific environment.

Methods of Risk Assessment

The following three methods of risk assessment have been used in the past in studies similar to this one:

1. Compute the probability of a worst-case event (e.g., the CRM).

2. Create a volume of airspace to account for deviation about the nominal flight path (e.g., TERPS obstacle clearance surfaces).

3. Create a volume of airspace with an explicit provision for blundering aircraft (e.g., Worst-Case Boundaries analysis).

SINGLE CRITERION BOUNDARY

The object of the proposed Single Criterion for converging approaches is to define a volume of airspace for aircraft flying missed approaches that provides an acceptable level of protection. In the event of simultaneous missed approaches, the Single Criterion also provides protection against a blundering aircraft.

The Single Criterion boundary is based on the following assumptions:

1. Assume that, although the probability is very small, eventually two aircraft will execute simultaneous missed approaches.

2. Assume that both aircraft fly straight ahead from the MAP for 1.5 nmi before turning.

3. Assume that one of the aircraft blunders. (That is, it fails to turn according to the published missed approach procedures.)

A combination of the Flight Simulation Study data and Project Lookout data was used for this analysis. The Johnson Su distribution was used for this analysis because it has been established that it fits the data better than the Gaussian distribution. This distribution is also more conservative, due to its thicker tails.

The Single Criterion boundary (shown in Figure D) consists of three elements: the straight boundary, turning boundary, and blunder protection. The result of combining these elements is a TERPS-shaped surface with additional protection against blunders.

The 1.5-nmi straight segment is protected by a boundary 6.6 standard deviations away from the nominal missed approach path. For a 200-foot DH, this results in a distance from the flight path to the boundary of 467 feet at the MAP and 1725 feet

Boundary Dimensions (200-ft. Decision Height)
— 1.5 nmi Straight Segment
— 467 ft. from Flight Path to Boundary at MAP
— 1,725 ft. from Flight Path to Boundary at Turning Point
    (7.9 Degree Divergence Angle)
— 1.75 nmi Turning Boundary Radius
    (1/2 Standard Rate Turn)

500 Ft. or Greater

Legend
Nominal Flight Path
Boundary of Protected Airspace
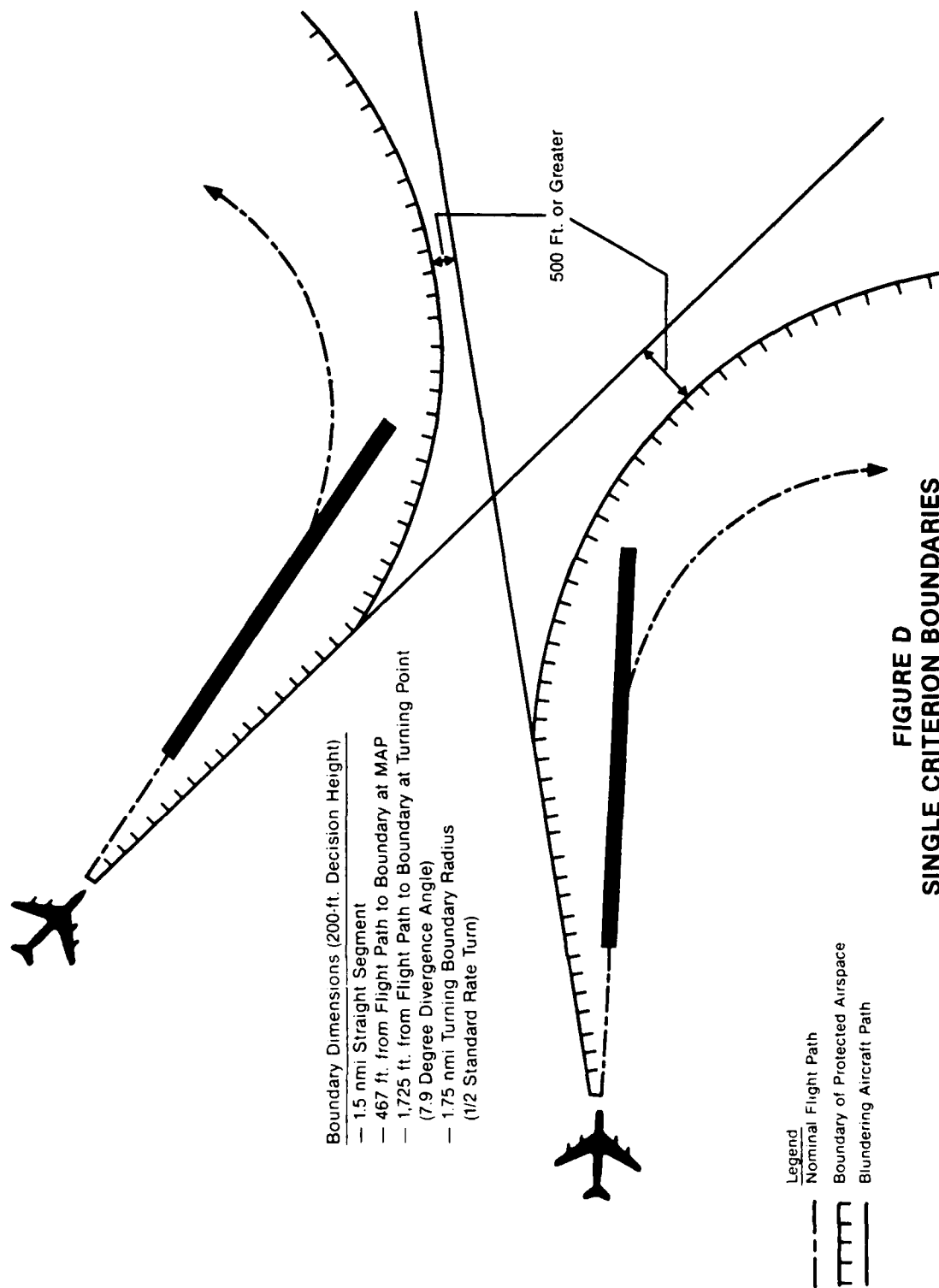Blundering Aircraft Path

FIGURE D
SINGLE CRITERION BOUNDARIES

at the turning point. (The probability of an aircraft being 6.6 standard deviations away from the nominal flight path, using the Johnson Su Distribution, is one in ten thousand.) The radius of the Turning boundary (1.75 nmi) corresponds to a half-standard-rate turn of a Category D aircraft.

The missed approach points are set so that the path of the blundering aircraft (estimated by the extension of the straight boundary) and the opposite boundary are separated by at least 500 feet.

COMPARISON OF CRITERIA

The size of the volume of airspace protected by the Single Criterion boundary is less than the volume protected by the TERPS surface (but greater than the volume protected by the Worst-Case Boundary). However, the TERPS+3 boundaries do not include an explicit provision for blundering aircraft. In addition to this provision, the Single Criterion boundaries include a distance of 500 feet between the potential path of a blundering aircraft and the opposite boundary.

The DHs computed for a group of the busiest U.S. airports, using the TERPS+3 interim criterion and the Single Criterion without the use of Navigational Aids (NAVAIDS) on missed approach, are shown in Table A.

These DHs were computed using a computer program, described in Appendix A, written in FORTRAN. This program computes the location of each boundary given an assumed DH. It then determines the distance between the boundaries, or that they intersect, and adjusts the DH accordingly. This process is repeated until the correct distance between the boundaries is achieved.

CONCLUSIONS

Table A shows that the DHs obtained using the Single Criterion are generally higher than those obtained using the TERPS+3 Criterion. This leads to the conclusion that, using the techniques described for the Single Criterion, DHs lower than those generated by the TERPS+3 Criterion may not be feasible for independent IFR approaches to converging runways. However, the Single Criterion may be useful in the future because it is directly related to aircraft performance on missed approach. Any improvements in navigation and/or aircraft performance can

TABLE A
DECISION HEIGHTS FOR DIFFERENT CRITERIA (IN FEET)

AIRPORT	CONVERGING RUNWAYS	SINGLE CRITERION	TERPS+3
Boston (BOS)	22R,27	885	670
Charlotte (CLT)	18R,23	875	710
Chicago (ORD)	22R,27L	640	515
	32L,27R	825	705
	9L,4R	425	430
	9R,4R	910	715
	9R,14L	515	390
	14L,22L	>1000	665
	14R,22R	>1000	705
	14R,22L	>1000	515
Dallas (DFW)	35L,31R	595	570
	35R,31R	705	640
	36L,31R	200	200
	36R,31R	200	200
Denver (DEN)	17L,26L	>1000	405
Detroit (DTW)	3R,9	910	665
	21R,27	>1000	740
Houston (IAH)	26,32R	685	410
Kansas City (MCI)	19,27	875	550
Las Vegas (LAS)	19L,25	860	550
Memphis (MEM)	36L,27	990	555
	36R,27	>1000	720
	36R,3	>1000	>1000
	21,18R	>1000	>1000
Miami (MIA)	27R,30	780	>1000
	9R,12	920	>1000
New Orleans (MSY)	10,19	>1000	770
Newark (EWR)	11,4R	>1000	690

TABLE A
(Concluded)

AIRPORT	CONVERGING RUNWAYS	SINGLE CRITERION	TERPS+3
New York (JFK)	13R,22L	>1000	535
	13L,4R	>1000	680
Oakland (OAK)	29,27L	205	>1000
Philadelphia (PHL)	9R,17	>1000	595
Salt Lake C. (SLC)	14,16L	>1000	>1000
	34L,32	>1000	>1000
Tampa (TPA)	27,18R	>1000	700

be reflected in the Single Criterion, with a corresponding lowering of DHs. Also, the use of existing NAVAIDS during missed approaches may allow a reduction in the amount of protected airspace required and/or the elimination of the requirement for blunder protection (the extended straight boundary). This would lead to lower DHs.

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1. INTRODUCTION

Several concepts for increasing airport capacity were developed in the late 1970s in response to the congestion present at major airports at that time (Reference 1). Continuing high levels of congestion have prompted further development of these concepts, leading toward their implementation in the near future. Implementing these concepts will increase capacity through more efficient use of airports and the surrounding airspace with the use of multiple approaches under Instrument Flight Rules (IFR) where it is not now permitted. At many airports, the implementation of these concepts could increase IFR capacity by as much as 100 percent, for some configurations under a given set of operating conditions.

One of these multiple-approach concepts is the operation of independent precision approaches to converging runways under IFR. The purpose of this report is to describe three criteria defining approaches to converging runways that are currently under consideration, and to propose a single criterion that would be acceptable to the aviation community.

1.1 Background

Approaches to converging runways are not allowed under IFR at this time. This is because, for the geometries considered in this report, the missed approach paths for the two runways would intersect. Although simultaneous missed approaches would be a rare occurrence, they are possible. Thus, although the arriving aircraft are separated on approach, if both were to execute straight missed approaches, a conflict between them could result. This possibility must be incorporated into the airspace design for each approach by providing airspace for turning missed approaches. Thus, the primary objective of any analysis of converging approaches is to provide a volume of protected airspace for aircraft executing simultaneous missed approaches such that conflicts are avoided.

Currently, approaches to converging runways are operated under Visual Flight Rules (VFR) for certain runway geometries, with controllers or pilots using visual separation on approach and missed approach. The concept of IFR approaches to converging runways was studied by The MITRE Corporation in 1981 (Reference 2). That study recommended both a volume of protected airspace and an explicit provision for an aircraft failing to follow the missed approach procedures. However, the concept was not readily accepted by the aviation community and other criteria were proposed.

1-1

One criterion proposed is the use of Tower-Applied Visual Separations on Missed Approach. But since this criterion involves visual separations, it has limitations. Another criterion is the application of Terminal Instrument Procedures (TERPS) obstacle clearance surfaces as a means of defining the volume of protected airspace. This criterion, with 3 nmi between missed approach points, has been proposed as an interim criterion by the Federal Aviation Administration (FAA).

1.2 Objective

Because it is important that pilots have a single procedure to follow on missed approach, the Industry Task Force on Airport Capacity Improvement and Delay Reduction led by the Airport Operators Council International (AOCI) has requested that a study be performed to generate one acceptable criterion. The study's objective is the re-examination of the proposed criteria and the design of one criterion for IFR converging operations that is both technically valid and acceptable to the aviation community.

1.3 Organization

Section 2 describes the concept of converging approaches in greater detail and the assumptions and analysis behind the three criteria currently under consideration. Section 3 reviews the data available on missed approaches and how previous studies have used that data. In addition, it focuses on methods used in the past to analyze the risk of flying missed approaches. Section 4 details the assumptions and analysis behind the proposed Single Criterion, while section 5 compares the Single Criterion to the TERPS+3 criterion and draws conclusions.

2. IFR APPROACHES TO CONVERGING RUNWAYS

IFR approaches to converging runways are defined as precision approaches to runways having an included angle of 15 to 100 degrees. (See Figure 2-1.) The runway pavement must either not intersect or intersect with a minimum distance of 8400 feet (for class D aircraft at elevations varying from sea level to 999 feet) from the thresholds to the intersection (Reference 3). Finally, both runways must be equipped with Instrument Landing Systems (ILSs) or Microwave Landing Systems (MLSs) for precision approaches.

When developing criteria for independent approaches to converging runways operating under IFR, the major design factor is the possibility of simultaneous missed approaches. Because straight missed approach flight paths would intersect, turning missed approach procedures must be designed. Several criteria have been proposed for protecting two aircraft executing missed approaches from approaches to converging runways. Because the size of the protected airspace varies between these criteria, the closest Missed Approach Point (MAP), and therefore the lowest Decision Height (DH), allowable may also vary.* These criteria are described in the following sections.

2.1 "Worst-Case Boundaries" Criterion

The analysis for the Worst-Case Boundaries assumes a remote, "worst-case" event and provides separation of the aircraft should that event occur (Reference 2). The "worst-case" is defined by the following assumptions:

1. Both aircraft simultaneously execute missed approaches.

2. Both aircraft stray from the localizer course by three standard deviations (of the lateral flight technical error) toward each other.

3. Both aircraft fly straight 1.5 nautical miles (nmi) before turning.

---

* For an ILS approach, the DH is the height at which a missed approach shall be initiated if visual contact with the runway environment has not been established. The MAP is the point in space where the glide path intersects the DH.

2-1

8400' or Greater*

8400' or Greater*
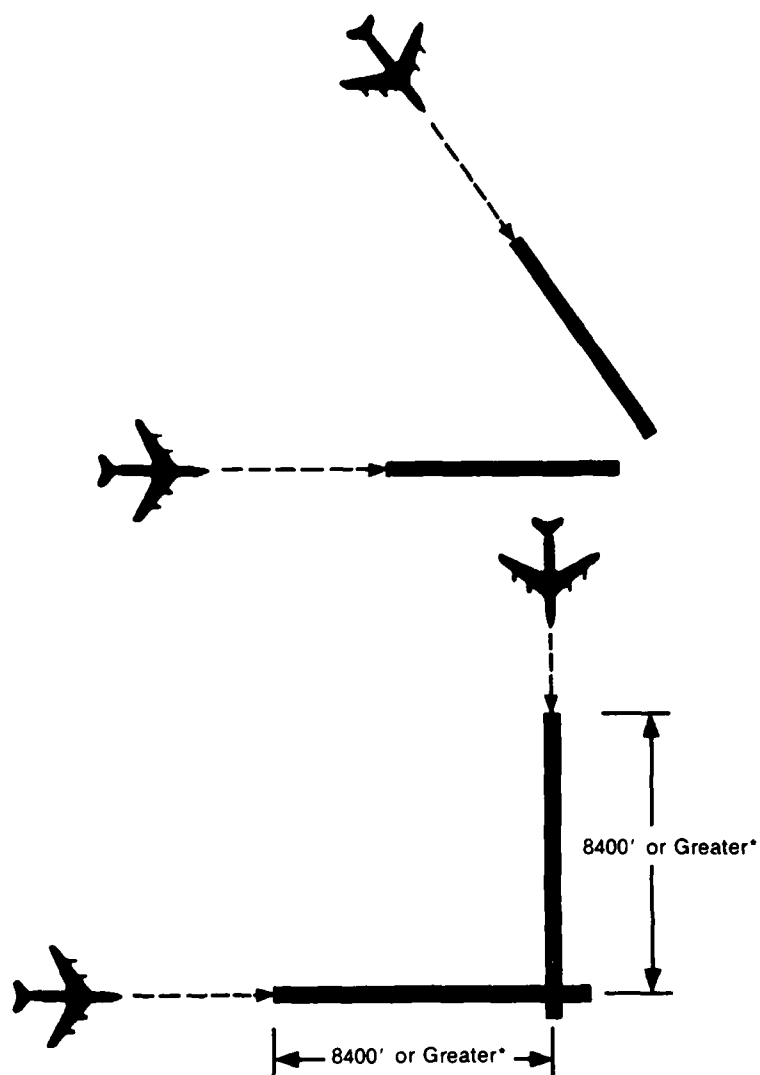
*Required for Class D aircraft at altitude varying from sea level to 999 feet.

FIGURE 2-1
TYPES OF APPROACHES TO CONVERGING RUNWAYS

4. Both aircraft are at the same altitude at the point of closest approach.

5. One aircraft blunders. (That is, it fails to turn according to the published missed approach procedures.)

6. The turning aircraft, with a ground speed of 165 knots, turns at only half the standard rate (1.5 degrees per second).

The Worst-Case Boundaries, shown in Figure 2-2, create a volume of protected airspace to account for the deviation of aircraft about the nominal flight path. Although aircraft are expected to stay within these boundaries a high percentage of the time, this analysis also contains a specific provision for a blundering aircraft. Note that the path of the blundering aircraft (the extended straight boundary) and the opposite turning boundary are separated by at least 500 feet.

To determine the DHs for the approaches to converging runways, the Worst-Case Boundaries are applied to a given pair of runways at the normal MAP. If the separation between the extended straight and curved boundaries measures less than 500 feet, a new MAP is computed which provides at least 500 feet separation. This results in an increase in the DH. IFR approaches to converging runways are proposed only when the ceiling is above this DH.

2.2 TERPS+3 Criterion

The TERPS+3 Criterion for converging approaches was proposed by the Industry Task Force on Airport Capacity Improvement and Delay Reduction and developed by FAA's Air Traffic Operations Service. This criterion applies TERPS obstacle clearance surfaces for turning missed approaches (Reference 4) to converging runways as a means of providing protected airspace. See Figure 2-3. A further requirement of this criterion is that the MAPs be adjusted, as needed, to provide at least 3 nmi between them. (It should be noted that nonoverlapping TERPS surfaces, without the 3-nmi separation between MAPs, have also been proposed as a criterion for converging approaches. However, this proposal is no longer under consideration.)

This criterion is applied in a manner similar to the Worst-Case Boundaries. The MAPs are adjusted to ensure that:

Boundary Dimensions (200-ft. Decision Height)

— 1.5 nmi Straight Segment
— 211 ft. from Flight Path to Boundary at MAP
— 943 ft. from Flight Path to Boundary at Turning Point
   (3.5 Degree Divergence Angle)
— 1.75 nmi Turning Boundary Radius
   (1/2 Standard Rate Turn)

FIGURE 2-2
WORST-CASE BOUNDARIES

2-4

Boundary Dimensions (200-ft. Decision Height)

— 1.5 nmi Straight Segment
— 1,042 ft. from Flight Path to Boundary at MAP
— 3,038 ft. from Flight Path to Boundary at Turning Point
    (12.4 Degree Divergence Angle)
— 3.5 nmi Turning Boundary Radius
    (1/4 Standard Rate Turn)
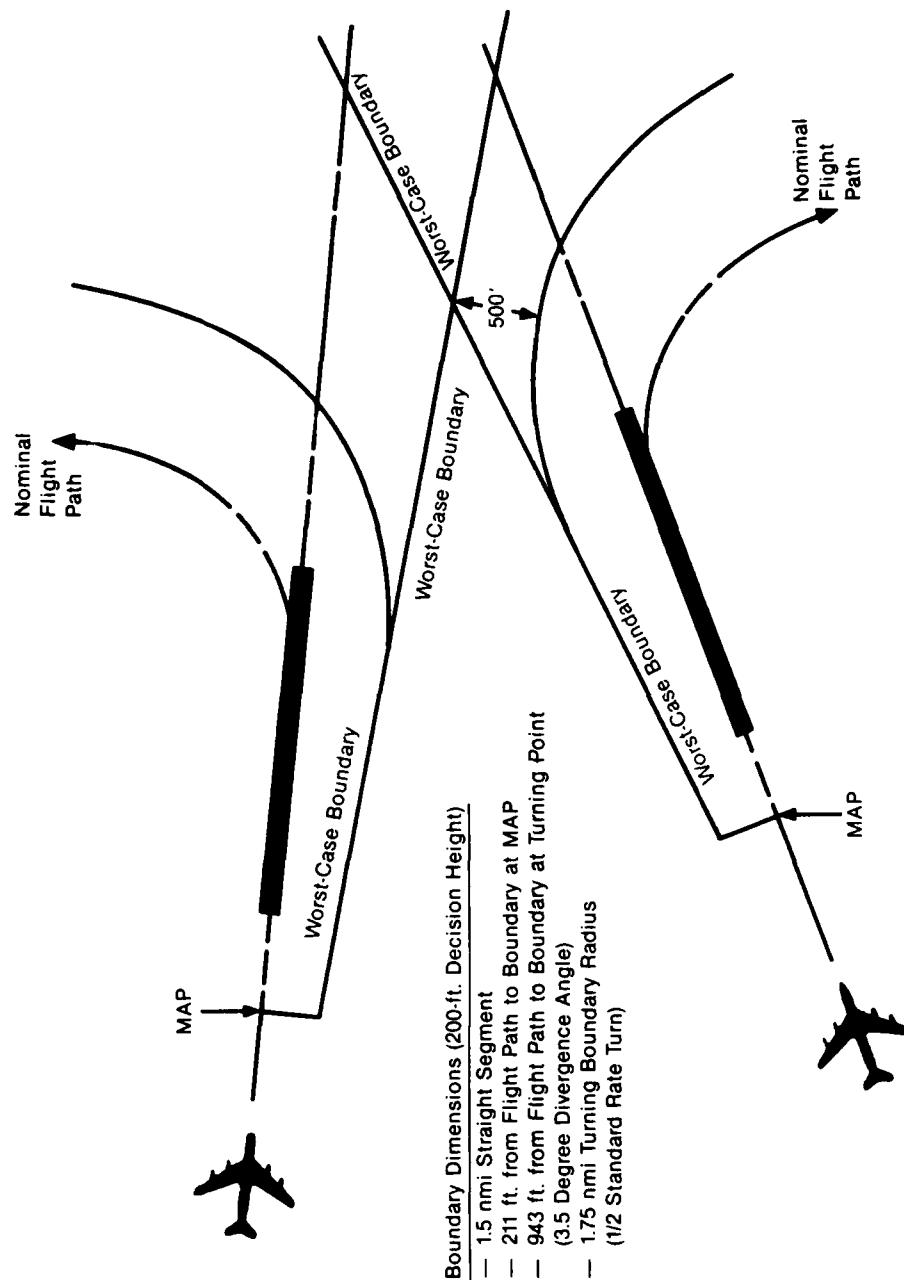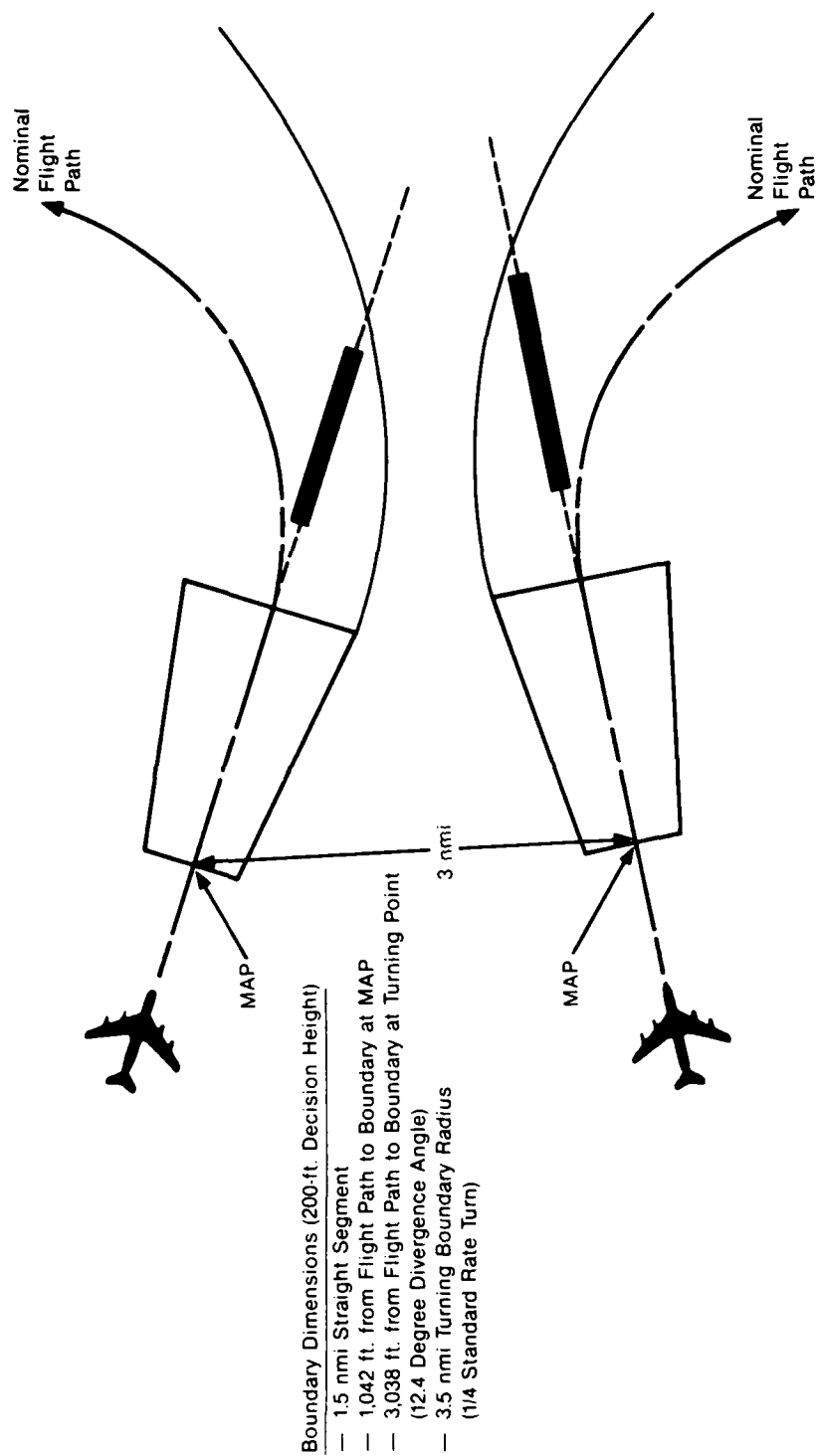
FIGURE 2-3
TERPS+3 BOUNDARIES

1. The turning missed approach surfaces do not overlap; and

2. The MAPs are separated by at least 3 nmi.

It is important to note that this criterion has no explicit provision for blundering aircraft and provides no horizontal distance between the surfaces beyond any that may be provided by the requirement of 3 nmi between MAPs.

2.3 Tower-Applied Visual Separation During Missed Approach

Converging approaches have been operated at Chicago's O'Hare International Airport for approximately 15 years using visual separation procedures. These procedures comprise the Tower Applied Visual Separation Criterion and are only applied when the ceiling is 700 feet Above Ground Level (AGL) or higher and the visibility is 2 nmi or greater. Figure 2-4 illustrates this criterion.

The procedures define one runway as "primary" and the other as "secondary." Aircraft on the primary runway use the standard DH for that approach, and are cleared to land independently from operations on the secondary runway. A "breakaway point" is defined on the secondary approach; it is the point where the secondary aircraft first comes within 3 nmi of the primary runway's localizer course. Aircraft on the secondary approach are cleared to land if, at the breakaway point, the pilot reports "runway in sight" and "landing assured" or if the tower controller has the aircraft in sight. If neither of these conditions is met, the tower controller issues a go-around order to the aircraft on the secondary approach.

If simultaneous missed approaches occur, this criterion calls for visual methods to maintain separation between the two aircraft. If the ceiling is low and the aircraft must remain below it so that the controller can provide visual separation, a difficult situation could develop.

2.4 Need for a Single Criterion

Although each of the proposed criteria can be (or has been) implemented, there are difficulties associated with using each of them for IFR approaches in Instrument Meteorological Conditions (IMC). Because many flight operations experts are intuitively uncomfortable with the size of the Worst-Case Boundaries, they have not been accepted by the aviation community. The TERPS+3 Criterion is based on the avoidance of
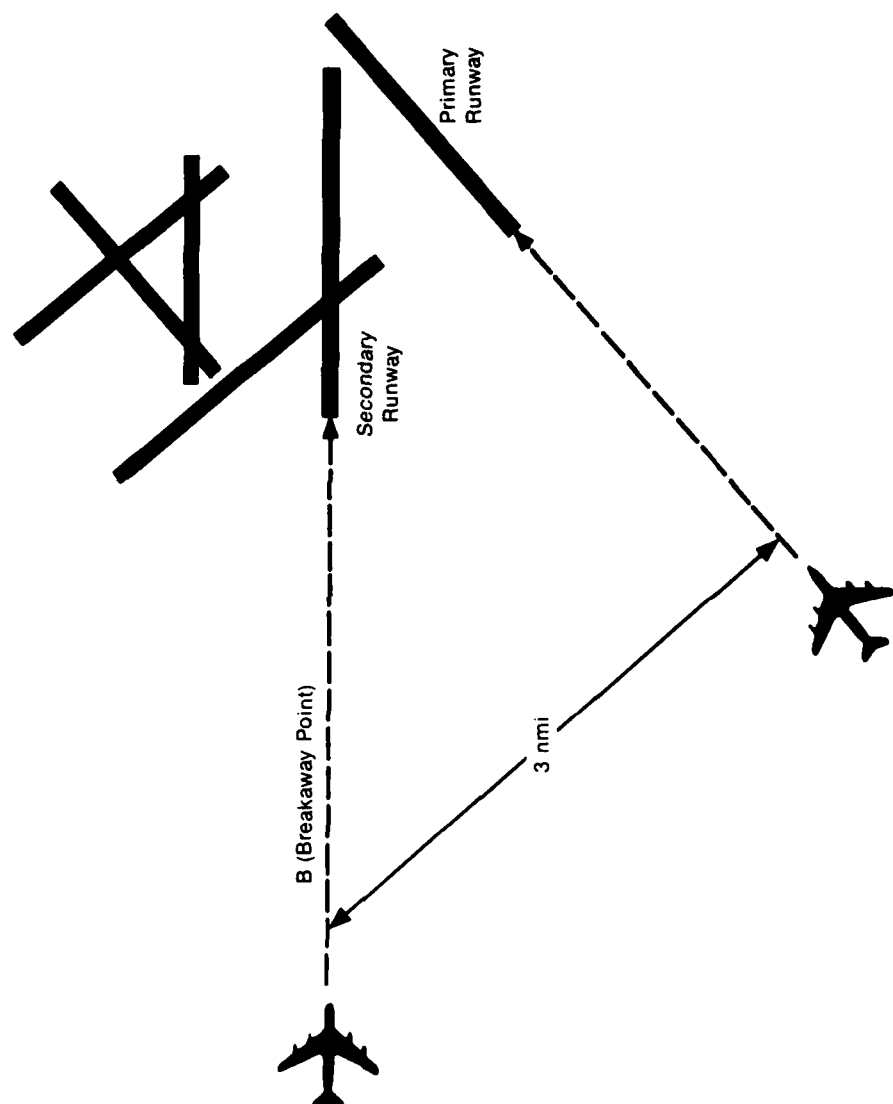
FIGURE 2-4
TOWER-APPLIED VISUAL SEPARATIONS

Primary Runway

Secondary Runway

B (Breakaway Point)

3 nmi

stationary obstacles below the surfaces rather than other air-craft, which are above the surfaces. Finally, Tower-Applied Visual Separations are based on visual separation during missed approaches. A problem with this procedure is that an aircraft executing a missed approach, after converting its descent to a climb, will be above the ceiling in a very short time; in this case visual separation could not be applied.

Because of the difficulties mentioned, and because it is important that pilots have a standard procedure to follow when executing a missed approach, the Industry Task Force on Airport Capacity Improvement and Delay Reduction has requested of the FAA that an analysis be performed to determine a Single Criterion for IFR converging approaches.

3. MISSED APPROACH DATA AND RISK ASSESSMENT

A critical element in the development of the Single Criterion is the data available on the position of aircraft flying missed approaches. Turning missed approaches must be flown from approaches to converging runways because the paths of aircraft executing simultaneous straight missed approaches would intersect. To assess the risk of flying these missed approaches, data on aircraft position on turning missed approach are necessary. However, no such data exist. Therefore, this study, like previous studies, must adapt the straight missed approach data in its analysis.

This section focuses on the existing data and previous studies that used it. These studies used several methods of analyzing the risk of flying missed approaches. One of these methods was the calculation of the volume of airspace necessary to protect aircraft at an acceptable level of risk. Another method used the physical characteristics around the airport (the position and height of obstacles) and aircraft performance characteristics to directly estimate the risk of collision while flying an approach/missed approach. Finally, one study included an explicit provision for the failure of one of two aircraft flying simultaneous missed approaches to follow published procedures.

3.1 Sources of Missed Approach Data

The following data exist on the lateral deviation of aircraft from the nominal flight path during straight missed approaches:

1. **Missed Approach Flight Simulation Study** -- This study, performed in 1975-1976, was designed specifically to generate data on the lateral and vertical dispersion of aircraft flying missed approaches and to generate probability density functions for those dispersions. Air carrier digital flight simulators located at the FAA Technical Center were used to generate the simulated missed approaches for which data were collected. The approaches were flown either autocoupled or using the flight director. Flight simulators for B747, DC10, B707, B727, DC9 and Cessna Citation aircraft types were used. Lateral and vertical aircraft position data were collected at the following points uprange and downrange from the runway threshold: +984 feet, +656 feet, +328 feet, 0 feet, -328 feet, -656 feet, -984 feet, -1969 feet, -2953 feet, and -3937 feet. The sample size at each of these ranges was approximately 120 observations. In addition, to verify the results of the simulation, 15 actual missed approaches were flown with an FAA B727 aircraft.

2. Project Lookout -- This study consisted of a series of flight tests conducted in 1965 by the FAA. Out of a total of 224 approaches, 179 missed approaches were recorded. Of the flights which resulted in missed approaches, 19 percent were autocoupled (for approach guidance), 35 percent used a flight director, and 46 percent used raw ILS information. The approaches were flown to a 100-foot DH on a 2.59 degree glide path by both piston-engined and jet aircraft.

3. United Kingdom Certification Data -- This study consisted of 168 missed approaches flown to a DH of 100 feet, but data were only recorded from the threshold to 1969 feet downrange.

Reference 4 describes all of the sources of data in greater detail.

3.2 Data Characteristics

The most salient characteristic of the data is the small sample size. Real-world data on missed approaches are nonexistent because of the overall scarcity of missed approaches, which are estimated to occur an average of 2 percent of the time (Reference 5). It is necessary for any analysis which attempts to determine airspace borders to estimate the maximum lateral deviation of aircraft from the nominal flight path. However, it is difficult to estimate that deviation accurately from such a small sample size. One method of resolving this is to assume a thick-tailed distribution, thus giving the analysis a conservative bias.

In addition to the sparseness, there are other problems with the data:

1. Most of the data were collected during Category II (CAT II) approaches, although the initial proposal for ILS converging approaches is concerned only with Category I (CAT I).

2. The data were recorded only a limited distance (less than 2 nmi) downrange from the MAP.

3. The largest body of data, from the Missed Approach Flight Simulation Study, was generated using simulators, rather than actual missed approaches.

4. All data recorded were from straight missed approaches.

3-2

Despite their problems and sparseness, these sets of data are the only sources of information on lateral deviation of aircraft on missed approach. Thus, they have been used in studies related to this one and are the basis for the Single Criterion developed in Chapter 4 of this report.

3.3 Previous Studies Using Missed Approach Data

Several related studies have used missed approach data for various purposes. The use of the existing data by these studies shows several methods of protected airspace design and risk assessment.

3.3.1 Worst-Case Boundaries

The Worst-Case Boundaries analysis combined the Flight Simulation and Project Lookout data to produce descriptive statistics on the distribution of lateral deviation about the nominal flight path on missed approach. The Flight Simulation data distributions describe the lateral flight technical error at various distances from the MAP to 2953 feet downrange from the runway threshold. The Project Lookout data distributions were used from 3937 to 8858 feet downrange from the threshold. These statistics were then combined to produce a boundary 3 standard deviations from the nominal flight path along the straight segment of the missed approach.

The analysis did not attempt to use the straight missed approach data to generate the turning boundary (which follows the straight boundary). Rather, this boundary corresponded to a half-standard-rate turn of the fastest aircraft which may fly the approach to provide a degree of conservatism over the expected standard turn rate.

By using the data distributions, the Worst-Case analysis produced a volume of protected airspace. In addition, it included an explicit provision for a blundering aircraft, which was not based on the data distributions (section 3.3.2, Reference 2).

3.3.2 TERPS Turning Missed Approach Surfaces

In a telephone conversation with the designers of the TERPS obstacle clearance surfaces at the FAA's Mike Monroney Aeronautical Center, it was learned that the TERPS surfaces were determined using the following:

1. Analysis based on aircraft characteristics, resulting in assumptions about how the aircraft will perform on missed approach;

2. Estimation based on the experience of the analysts; and

3. Analysis of valid statistical data generated by flight tests.

It is important to note that there are not enough observations in the data analyzed to constitute a statistically valid data base. Rather, the analysts "looked at" data on aircraft dispersion on missed approaches to help determine the size of the surfaces.

The radius of the turning boundary corresponded to the radius of a quarter-standard-rate turn (0.75 degrees/second) for the design aircraft. This figure was not based on statistical analysis but was a "reasonable and conservative figure" based on the experience of the analysts and their knowledge of pilot technique and the operational situation. A conservative boundary was deemed necessary since the 400-foot (AGL) height at the start of the turn does not allow a large margin for pilot error.

The outcome of the TERPS analysis was a volume of airspace protected from stationary obstacles. This volume of airspace was generated from both formal risk assessment, based on aircraft performance and behavioral data; and informal risk assessment, based on the experience of the analysts.

3.3.3 Collision Risk Model

The International Civil Aviation Organization (ICAO) Collision Risk Model (CRM, Reference 6) generates a numerical estimate of the risk of collision that is a result of the obstacle environment surrounding the approach and missed approach and a given obstacle clearance height. The risk associated with individual obstacles may also be determined, and the user may vary any of the characteristics of the approach or missed approach to determine the effects on risk.

The final approach section of the CRM is based on data collected primarily from CAT II approaches using either an autopilot or flight director. A mathematical model of an ILS system was then developed, which related lateral displacements about the approach course to errors in components of the ILS and to the

degree of coupling between the aircraft and the ILS signals. This model was then matched to the data and used to produce distributions of the displacement of aircraft about the approach course. This data is used to compute the width of the protected airspace at the MAP.

The missed approach section of the CRM consists of two elements: the vertical and lateral distributions of aircraft. The vertical distributions describe aircraft performance during the initial phase of a missed approach. These distributions are used to estimate the height loss of the aircraft as the pilot transitions from descent to climb.

The distributions of lateral displacement about the nominal missed approach path are based directly on data. Because the navigational guidance available at the beginning of the missed approach may be ignored by the pilot (as the aircraft is stabilized and its ascent begins), the characteristics of the ILS are not a major factor. The data from which the distributions were generated were not collected under actual IMC, and have been described in section 3.1.

The Gaussian distribution did not fit the data; it showed a tendency to underestimate the probabilities of large deviations. In Reference 8, Pate applied a goodness-of-fit test and determined that the Johnson Su distribution was the most representative. Beyond the limits of the data, it produced higher probabilities of large displacements than the Gaussian distribution.

The distributions generated for lateral dispersion of aircraft on missed approach were limited to the range from 984 feet before the threshold to 3937 feet beyond it (for straight missed approaches only). The use of the CRM past the 3937-foot point is accomplished through linear extrapolation.

The CRM generates a numerical estimate of the risk of collision between an aircraft and an obstacle for a specific environment. Both the characteristics of the physical environment (that is, obstacle size and location) and the approaches/missed approaches may be varied within the model. These characteristics are varied until an environment with an acceptable level of risk is produced.

3-5

3.4 Methods of Risk Assessment

The following are three methods of risk assessment that have been used in the past in studies similar to this one:

1. Compute the probability of the worst-case event (e.g., ICAO CRM).

2. Create a volume of airspace to account for deviation about the nominal flight path (e.g., TERPS obstacle clearance surfaces).

For this method, aircraft are expected to fly within the protected airspace a very high percentage of the time. There is no explicit provision for blundering aircraft, although surveillance is used to assist in detecting blunders. It should be noted that aircraft leaving this airspace are not guaranteed protection.

3. Create a volume of protected airspace with an explicit provision for blundering aircraft. For example, in the analysis performed in Independent Parallel Instrument Approaches at Reduced Runway Spacing (Reference 7), a Normal Operating Zone was defined such that the likelihood of an aircraft being observed outside of it was very small. Additional spacing was then required between the two parallel runways to take into account the possibility of one aircraft blundering toward the opposite approach. Another example of this type of analysis is the previously described Worst-Case Boundary analysis.

3-6

4.   SINGLE CRITERION DEFINITION

The method used to define a Single Criterion for IFR approaches
to converging runways is Method 3 (described in section 3.4).
This method not only defines a volume of airspace designed to
provide an acceptable level of protection to normal operations,
but also provides protection against a blundering aircraft.
Thus both analytical and intuitive concerns are taken into
account by this method. The proposed Single Criterion uses a
methodology that addresses all of the issues raised with IFR
approaches to converging runways.

4.1 Assumptions

The following are the assumptions underlying the Single
Criterion analysis:

> 1. Assume that, although the probability is very small,
> eventually two aircraft will execute simultaneous missed
> approaches.

> 2. Assume that both aircraft fly straight ahead from the
> MAP for 1.5 nmi before turning.

>> a. To allow the aircraft to stabilize

>> b. To allow the aircraft to climb to 400 feet AGL
>> before starting turn

>> c. To allow for missed approaches which begin after
>> the MAP

> 3. Assume that one aircraft blunders. (That is, it fails
> to turn in accordance with the published turning missed
> approach procedures.)

4.2 Data Distribution

The product of this analysis will be a volume of protected
airspace for aircraft flying missed approaches. This airspace
will be designed such that the probability that an aircraft
will be at or beyond the boundary of its protected airspace is
one in ten thousand. (This conditional probability, coupled
with assumptions listed above, produces an extremely low
absolute probability of a near midair collision.)

The Johnson Su distribution, rather than the Gaussian distribution, is used in this analysis. This is because, in goodness-of-fit tests performed by Pate (Reference 8), the Johnson Su distribution fit the data better than the Gaussian distribution. It should also be noted that this distribution is much more conservative than the Gaussian distribution due to its shape; it can be described as having "thicker tails." Using this distribution, the probability of being more than 6.6 standard deviations from the mean is equal to one in ten thousand. (As a basis for comparison between the two distributions, note that for the Gaussian distribution, the probability of being only 3.9 standard deviations from the mean is one in ten thousand.)

4.3 Elements of the Single Criterion Boundary

The elements of the Single Criterion boundary and the protected airspace are shown in Figure 4-1 and can be described as follows:

1. MAP -- The Missed Approach Point is the point on the approach below which descent may not continue without visual reference. For a precision approach, this point is the intersection of the DH and the glide slope.

2. Nominal Flight Path -- This is the expected path to be followed by an aircraft executing a missed approach. It consists of a 1.5-nmi straight segment followed by a turning segment consisting of a standard-rate turn for a Category D aircraft (the design aircraft).

3. Turning Point -- This is the point on the nominal flight path at which the aircraft begins its turn away from the other approach.

4. Straight Boundary -- This is the boundary of the protected airspace adjacent to the straight segment of the flight path.

5. Turning Boundary -- This is the boundary of the protected airspace adjacent to the turning segment of the nominal flight path.

6. Blundering Aircraft Path -- This is the hypothetical path of an aircraft which fails to turn according to the published procedures.
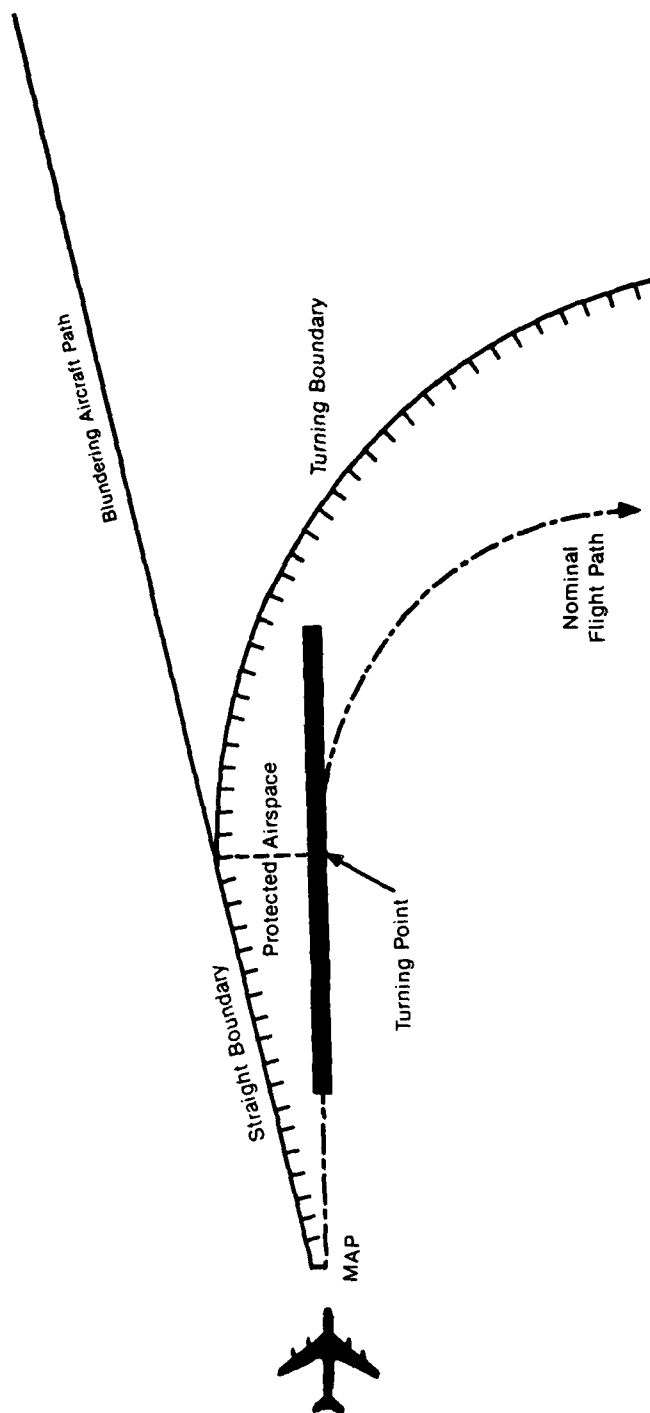
FIGURE 4-1
ELEMENTS OF THE SINGLE CRITERION BOUNDARY

7. Protected Airspace -- This is the airspace encompassed by the straight and turning boundaries. It is "protected" in the sense that other aircraft are procedurally restricted from entering it and thereby threatening the aircraft executing the missed approach.

4.4 Single Criterion Boundary Construction

The Single Criterion boundary consists of three elements: the straight boundary, turning boundary, and blunder protection. The result of combining these elements is a TERPS-shaped surface with additional protection against blunders, shown in Figure 4-2.

The straight boundary is designed to protect against the deviation of aircraft about the nominal flight path during the 1.5-nmi straight segment of the missed approach. A certain amount of deviation is expected since, during this phase of the missed approach, the pilot is more concerned with keeping the wings level and gaining altitude than with navigating the missed approach course exactly. The straight boundary begins at the MAP at a distance corresponding to 6.6 standard deviations (of the distribution applicable at that range on the approach) toward the other approach (467 feet for a 200-foot DH). The boundary continues in a straight line 6.6 standard deviations from the nominal flight path for the length of the straight segment. Since the deviation of aircraft from the nominal flight path tends to increase as they fly a straight missed approach, the distance from the flight path to the boundary increases through the length of the straight segment. (At the end of the straight segment, the boundary is 1725 feet from the nominal flight path for a 200-foot DH.)

The turning boundary is designed to protect aircraft executing the turning segment of the missed approach. The boundary consists of an arc beginning at the end of the straight boundary. The arc is constructed to correspond to a half-standard-rate turn for a Category D aircraft. (The radius of the arc is 1.75-nmi.)

The blunder protection segment is designed to protect against the failure of one of the two aircraft to turn while executing simultaneous missed approaches. It is assumed that the aircraft failing to turn has been traveling a path corresponding to the straight boundary. Thus, that aircraft's path is an extrapolation of that boundary beyond the turning point. Blunder protection is provided by situating the boundaries such that a distance of 500 feet separates the path of the blundering aircraft and the boundary of the opposite missed approaches' protected airspace. If necessary, the DHs are raised; this moves the MAPs back and the two volumes of protected airspace apart.

4-4

Boundary Dimensions (200-ft. Decision Height)

— 1.5 nmi Straight Segment
— 467 ft. from Flight Path to Boundary at MAP
— 1,725 ft. from Flight Path to Boundary at Turning Point
   (7.9 Degree Divergence Angle)
— 1.75 nmi Turning Boundary Radius
   (1/2 Standard Rate Turn)

500 Ft. or Greater

Legend

Nominal Flight Path
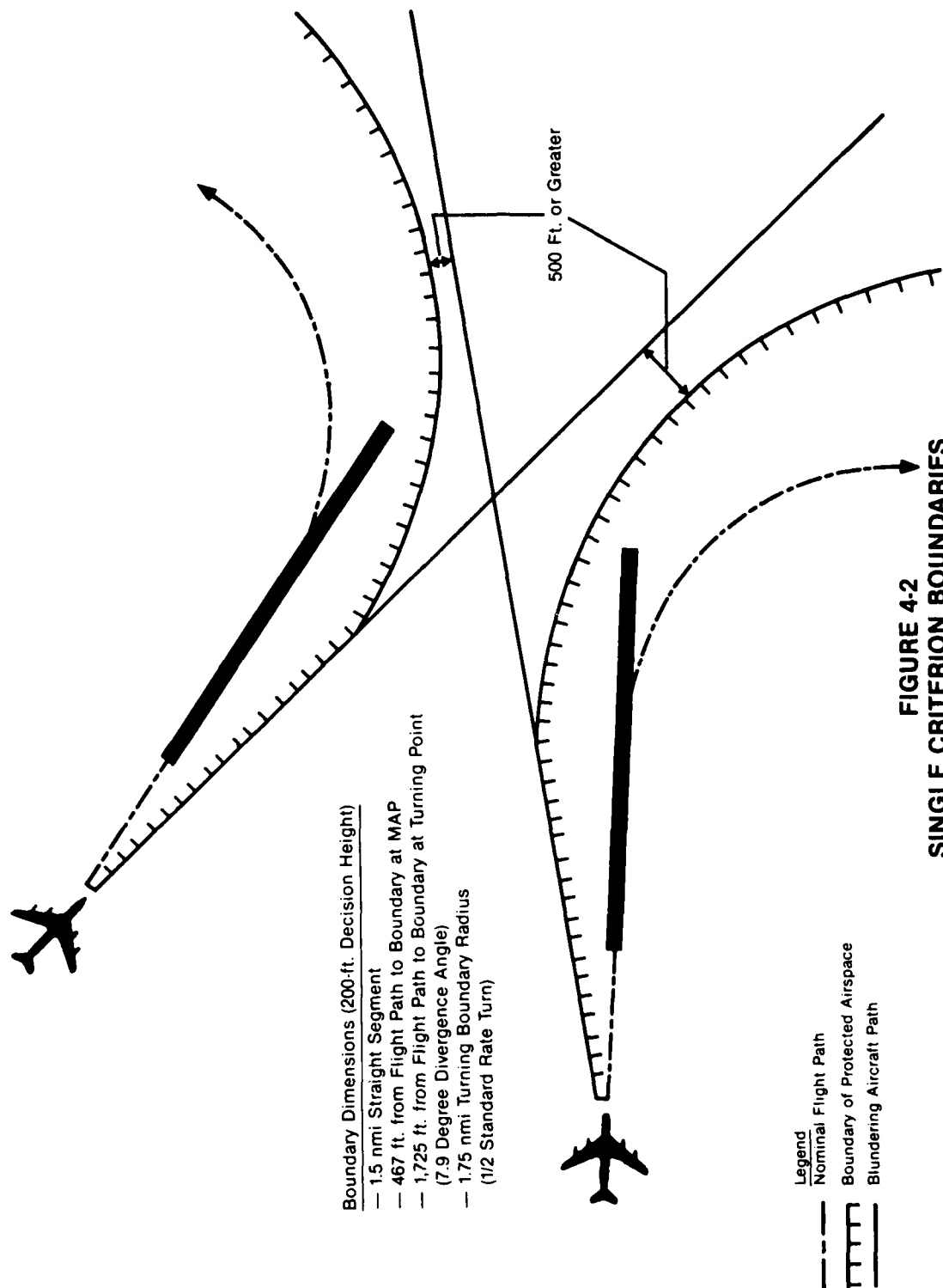Boundary of Protected Airspace
Blundering Aircraft Path

FIGURE 4-2
SINGLE CRITERION BOUNDARIES

4-5

If this criterion is satisfied, it can be shown that for any converging runway geometry, the nominal flight paths are never closer than 3950 feet. (This number is composed of twice the 1725-foot width at the turning point plus the 500-foot miss distance.)

5. COMPARISON AND CONCLUSIONS

In this section, the size of the volumes of protected airspace and the DHs generated by the Single Criterion and TERPS+3 Criterion are compared. This is followed by conclusions and suggestions for further research.

5.1 Comparison of Criteria

The size of the volume of airspace protected by the Single Criterion boundary is less than the volume protected by the TERPS surface (but greater than the volume protected by the Worst-Case Boundary; see Figure 5-1). At the MAP, for a 200-foot DH, the distance from the nominal flight path to the boundary for each criterion is:

1. 467 feet -- Single Criterion Boundary

2. 1042 feet -- TERPS+3 Boundary

At the turning point, also for a 200-foot DH, the distances are:

1. 1725 feet -- Single Criterion Boundary

2. 3038 feet -- TERPS+3 Boundary

It is important to note that, in all cases, the minimum distance between nominal flight paths is at least twice the distance from either flight path to the boundary at the turning point (for the Single Criterion, this distance is 3950 feet).

It should also be noted that the TERPS+3 boundaries do not include an explicit provision for blundering aircraft. In addition to the provision for a blundering aircraft, the Single Criterion Boundaries include a distance of 500 feet between the potential path of a blundering aircraft and the opposite boundary.

5.2 Decision Heights

The DHs computed for a group of the busiest U.S. airports, using the TERPS+3 Criterion and the Single Criterion, are shown in Table 5-1.

These DHs were computed using a computer program, described in Appendix A, written in FORTRAN. This program computes the location of each boundary given an assumed DH. It then determines the distance between the boundaries, or that they

5-1

Legend
TERPS+3 Boundary
Single Criterion Boundary
Worst-Case Boundary
Nominal Flight Path
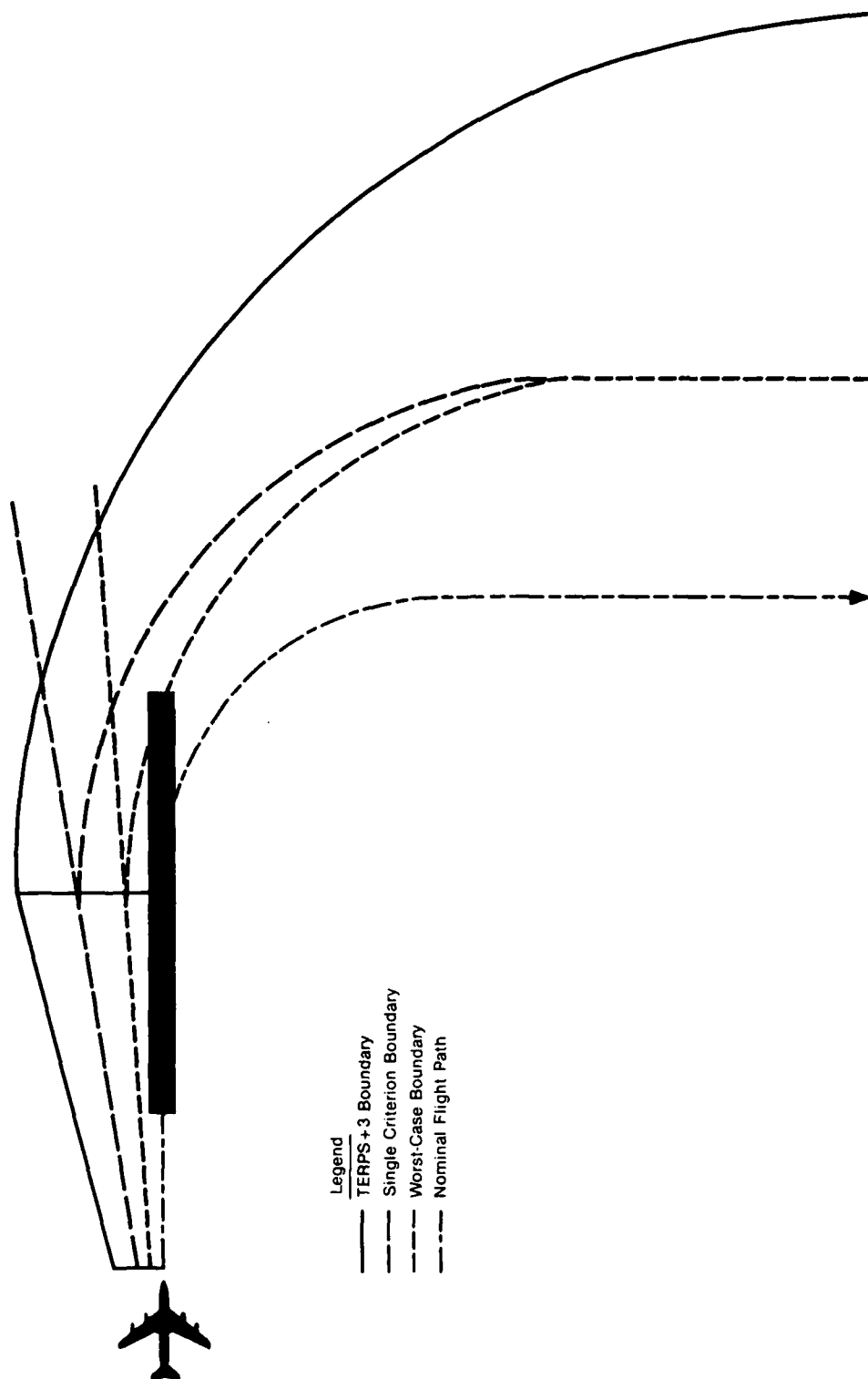
FIGURE 5-1
COMPARISON OF CRITERIA

5-2

TABLE 5-1
DECISION HEIGHTS FOR DIFFERENT CRITERIA (IN FEET)

AIRPORT	CONVERGING RUNWAYS	SINGLE CRITERION	TERPS+3
Boston (BOS)	22R,27	885	670
Charlotte (CLT)	18R,23	875	710
Chicago (ORD)	22R,27L	640	515
	32L,27R	825	705
	9L,4R	425	430
	9R,4R	910	715
	9R,14L	515	390
	14L,22L	>1000	665
	14R,22R	>1000	705
	14R,22L	>1000	515
Dallas (DFW)	35L,31R	595	570
	35R,31R	705	640
	36L,31R	200	200
	36R,31R	200	200
Denver (DEN)	17L,26L	>1000	405
Detroit (DTW)	3R,9	910	665
	21R,27	>1000	740
Houston (IAH)	26,32R	685	410
Kansas City (MCI)	19,27	875	550
Las Vegas (LAS)	19L,25	860	550
Memphis (MEM)	36L,27	990	555
	36R,27	>1000	720
	36R,3	>1000	>1000
	21,18R	>1000	>1000
Miami (MIA)	27R,30	780	>1000
	9R,12	920	>1000
New Orleans (MSY)	10,19	>1000	770
Newark (EWR)	11,4R	>1000	690

TABLE 5-1
(Concluded)

AIRPORT	CONVERGING RUNWAYS	SINGLE CRITERION	TERPS+3
New York (JFK)	13R,22L	>1000	535
	13L,4R	>1000	680
Oakland (OAK)	29,27L	205	>1000
Philadelphia (PHL)	9R,17	>1000	595
Salt Lake C. (SLC)	14,16L	>1000	>1000
	34L,32	>1000	>1000
Tampa (TPA)	27,18R	>1000	700

intersect, and adjusts the DH accordingly. This process is repeated until the correct distance between the boundaries is achieved.

5.3 Implementing a Criterion

A prerequisite to the operation of IFR approaches to converging runways is that precision approach guidance must be available on both approaches (to minimize the number of missed approaches). In addition, a separate approach plate should be published which details the turning missed approach course and the higher DHs (if applicable). The appropriate changes should also be made to the air traffic controller's handbook. Finally, pilots should be advised that converging approaches are in use.

5.4 Conclusions

Table 5-1 shows that the DHs obtained using the Single Criterion are generally higher than those obtained using the TERPS+3 Criterion. This leads to the conclusion that, using the techniques described for the Single Criterion, DHs lower than those generated by the TERPS+3 Criterion may not be feasible for independent IFR approaches to converging runways. However, the Single Criterion may be useful in the future because it is directly related to aircraft performance on missed approach. Any improvements in navigation and/or aircraft performance can be reflected in the Single Criterion, with a corresponding lowering of DHs. Also, the use of existing Navigational Aids (NAVAIDS) during missed approaches may allow a reduction in the amount of protected airspace required and/or the elimination of the requirement for blunder protection (the extended straight boundary). This would lead to lower DHs.

APPENDIX A

COMPUTER PROGRAM FOR COMPUTING DECISION HEIGHTS

Several criteria for determining the minimum DH allowed for IFR approaches to converging runways are currently under consideration by the FAA. These criteria, the Worst-Case Boundaries, TERPS+3, and the Single Criterion, define boundaries that create a volume of protected airspace for an aircraft flying a missed approach when approaches to converging runways are in use. The application of any of these three criteria to a specific pair of runways results in a DH for operating these approaches.

A.1 Applying the Criteria

Previously, the DHs for specific sites were estimated by obtaining Airport Layout Plans (ALPs) drawn to scale and using boundaries, also drawn to scale, on transparencies. These transparencies were placed on the ALP and maneuvered until the parameters described for the criteria above were met. The distance to the MAP was then measured and the DH computed from that.

There were two problems associated with that method. The first was that the accuracy of transparencies and copies of ALPs was limited. The second was that, for all criteria, the distance from the nominal flight path to the boundary at the MAP varies. (The variability is relative to the lateral dispersion of aircraft on final approach at that range from the threshold.) This variability could only be taken into account by drawing a separate transparency for every possible DH.

The computer program described in this appendix applies any (or all) of these three criteria to a specific pair of converging runways and produces a DH according to the parameters described above. Only simple inputs describing the runway geometry are required.

A.2 Using the Program

The program, named CVG, executes on an IBM PC-XT personal computer. It is accessed by using the appropriate Disk Operating System (DOS) commands to access the floppy disk or enter the hard-disk directory in which the program resides.

A-1

A.2.1   Running the Program without Debugging Information

The program is run by entering the command

    CVG

The program then prompts the user for the necessary information.
The first prompt is to determine if debugging information is
desired:

    Do you want debug output?

If the user desires debugging information, he must respond to
this prompt with a "y" or "Y" (no quotes).

The user is then prompted for the type of analysis to be
performed:

    Select the type of analysis desired (1, 2, or 3):

    1.   Single Criterion
    2.   Worst-Case Boundaries
    3.   TERPS+3

The user responds with the number that indicates the type of
analysis.

Next, the user is prompted for the runway lengths, which must
be entered as integers:

    Enter the runway lengths in feet:

The user is then prompted for the angle between the runways,
which may be entered as either an integer or decimal number:

    Enter the included angle in degrees:

Finally, the program prompts the user for the distance from
each runway end to the intersection of the extended runway
centerlines. (See figure A-1.) If the runways intersect, or
if the extended centerline of one runway intersects the other
runway, the distance from the intersection to the runway end is
a negative number. (All distances must be integers.)

    Enter the distance (in feet) from the departure end of
    runway 1 and from the departure end of runway 2 to the
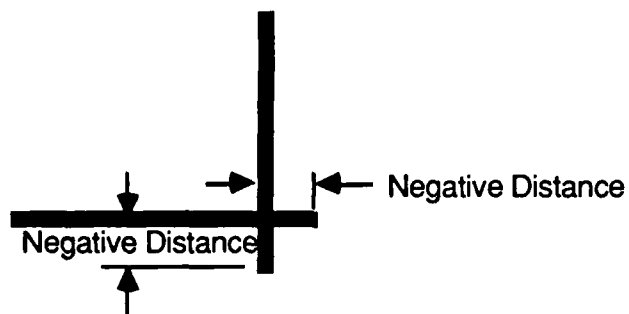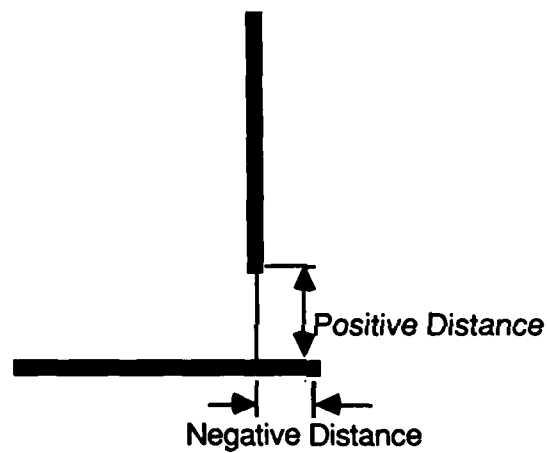   intersection:
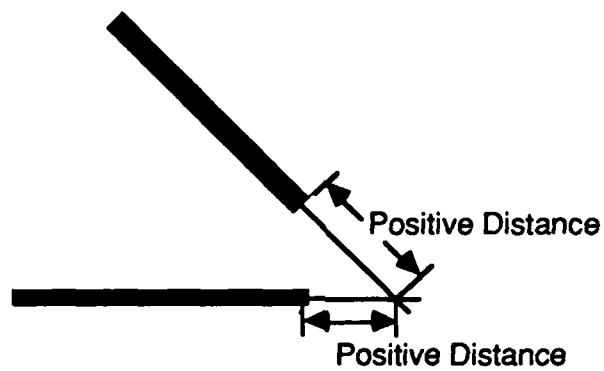
FIGURE A-1
DISTANCE FROM RUNWAY END TO INTERSECTION

A~3

The program then responds with the DH:

The DH is 556 feet.

Following this result, the program prompts the user for further action:

Do another case?

If the user responds with "y" or "Y", the process is repeated, beginning with the prompt for the type of analysis desired. In addition, each time the input process is repeated, the user has the option of re-entering the inputs that define the runway configuration or retaining those used previously.

A.2.2 Running the Program with Debugging Information

If the debugging option is chosen, all information described above is produced by the program, along with the following information:

1. The coordinates of the runway ends;

2. The current DH (the DH for which the program is currently checking the separation);

3. The distance from the nominal flight path to the boundary at the MAP (This is the variable MAPWDn, where n is 1 or 2, representing runway 1 or runway 2.);

4. The coordinates of the MAPs are displayed if the TERPS+3 analysis has been chosen (XMAPn, YMAPn);

5. The coordinates of points A and B on both boundaries (XBnA, YBnA, XBnB, YBnB);

6. The coordinates of the intersection (XBINT, YBINT);

7. The distance from point A to the intersection (Dn);

8. The threshold-to-MAP distance (THMAPn);

9. The included angles between the runways and boundaries (THETA and THETAP, respectively);

10. The angle of divergence of the boundary, which applies only to Single Criterion and Worst-Case Boundaries (ALPHA);

A-4

11. The new coordinates resulting from the shifting of the coordinate system in Subroutine Switch;

12. Where the two boundaries intersect, if applicable;

13. Where the minimum separation between the boundaries occurs (that is, between two arcs or between an arc and a line); and

14. The current minimum separation.

The following is a sample of the debugging output for the final DH iteration of Chicago O'Hare's runways 22R and 27L (Single Criterion). The points described in the output are shown in Figure A-2:

```
The current DH is 642.2

Subroutine Coords:
MAPWD1          835.7549000 MAPWD2          835.7549000
XB1A     -11299.6100000 YB1A          835.7549000
XB1B      -2264.2070000 YB1B         2030.1020000
XB2A      -1950.4440000 YB2A        17112.9200000
XB2B       2942.4790000 YB2B         9423.6880000
XBINT      6878.2630000 YBINT        3238.6010000
D1     18336.0000000 D2       16445.1400000
THMAP1     11299.6100000 THMAP2       11299.6100000
THETA  8.726646E-001 THETAP          1.1355110
ALPHA  1.314233E-001

Subroutine Switch:
X1A       -9114.0000000 Y1A         10633.0000000
X1B            .0000000 Y1B         10633.0000000
X2A        2287.5900000 Y2A         25544.6300000
X2B        6130.6820000 Y2B         17280.5200000
X2C       15772.1500000 Y2C         21764.1200000
XINT       9221.9980000 YINT        10633.0000000

The min. sep. is between line 1 and arc 2:
X1F      15772.1500000 Y1F         10633.0000000
X2F      15772.1500000 Y2F         11131.1200000
The current separation is          498.1211000

The DH is 642 feet.
```

FIGURE A-2
CRITICAL POINTS ON THE BOUNDARIES

A.3 Program Design

The program is written in FORTRAN 77 and is designed in a modular style.

A.3.1 Program Functions

The following actions are the basic steps taken by the program:

1. Variables are initialized and inputs are requested from the user.

2. A DH is assumed.

3. The coordinates of critical points on the boundaries are calculated.

4. To eliminate a case that would otherwise have to be analyzed later in the program, the runway coordinates are interchanged if the straight segment of boundary 2 is longer than the straight segment of boundary 1.

5. Cases where the boundaries intersect are trapped and control is returned to the main program.

6. The minimum separation between boundaries is calculated.

7. If the minimum separation is equal to the required minimum separation, the program displays the resulting DH and waits for further instruction from the user.

8. If the minimum separation is too small or the boundaries intersect, the DH is increased and the process is repeated beginning with step 3.

9. If the minimum separation is too large, the DH is decreased and the process is repeated beginning with step 3.

A.3.2 Logic Description

Each routine of the program is described in detail in the sections below.

A.3.2.1 Main Routine

The main routine of the program first defines all parameters having to do with the analysis and the three criteria. (These parameters are defined in PARAMETER statements rather than in an input file for ease of use and transportability. This was done because it was not expected that these parameters would change often and it is easy to change them and recompile the program.) For example, the minimum and maximum allowable DHs and the sizes of the boundaries are defined here. It should also be noted that all boundary-specific variables are defined separately for runways 1 and 2; this was done so that different characteristics for each approach might be accommodated. (For example, an approach to a separate, short, converging runway could be defined separately from the approach to the main runway.)

Variables are then initialized, and the user is prompted for his choice of debug/no debug and the type of analysis desired. The parameters specific to the type of analysis are then transferred over to the variables to be used in the program.

Subroutine Input is then called to obtain the runway geometry inputs. Subroutine Coords then computes the boundary coordinates, and Subroutine Switch interchanges those sets of coordinates if necessary. Subroutine Trap is then called, which checks for intersecting boundaries and, in the TERPS+3 case, for MAPs less than 3 nmi apart. Finally, if Trap has not found either of these conditions to be true, Subroutine Minsep is called. Minsep computes the minimum separation between the boundaries and returns to the main program.

At this point the main program's convergence algorithm begins. If the boundaries intersect or the separation returned from Minsep is too low, the lower limit of the convergence algorithm is set to the current DH and the DH is then increased. If the separation returned from Minsep is too high, the higher limit of the convergence algorithm is set to the current DH and the DH is then decreased.

The DH is always increased or decreased to the average of the current value and the applicable limit. This algorithm generally converges in 12 iterations or less. Note that the separation need only be within ± 2 feet of the target separation, since the effect of this inaccuracy on the DH is negligible. (The only exception to the ± 2 feet rule is the separation for the TERPS+3 Criterion, which is allowed to vary from 0 to 4 feet.)

A-8

Once the final DH has been found, it is displayed and the user is prompted for further action.

A.3.2.2 Subroutine Input

This routine requests from the user the runway lengths, angle between the runways, and the distance from each runway departure end to the intersection. (Note that if the intersection is within the length of one or both runways, the distance(s) must be negative.) The runway-end coordinates are then computed and displayed if the debug option has been chosen. The runway-end coordinates are calculated as follows:

```
X1TH    = 0
Y1TH    = 0
X1DEND  = RWY1
Y1DEND  = 0
X2TH    = (RWY1 + DEND1P) - COSTH * (RWY2 + DEND2P)
Y2TH    = SINTH * (RWY2 + DEND2P)
X2DEND  = X2TH + COSTH * RWY2
Y2DEND  = Y2TH - SINTH * RWY2
XINT    = X1DEND + DEND1P
YINT    = 0
```

where:

```
XnTH    = x-coordinate (x-coord) of the runway n threshold
YnTH    = y-coord of the runway threshold
DENDnP  = distance from departure end of runway n to the
          intersection of the runway centerlines
XnDEND  = x-coord of the runway departure end
YnDEND  = y-coord of the runway departure end
RWYn    = length of runway n
COSTH   = cosine of the angle (theta) between the runways
SINTH   = sine of the angle between the runways
XINT    = x-coord of the intersection of the runway center-
          lines
YINT    = y-coord of the intersection of the runway center-
          lines
```

A.3.2.3 Subroutine Coords

This routine first calculates the threshold-to-MAP distance for each approach:

```
THMAPn = (DH - 50.) / TANGSn
```

where:

TANGSn = the tangent of the glide slope angle for runway n

This is followed by the calculation of the lateral distance from the MAP to the starting point of the boundary (point BnA). These equations, for the Single Criterion and Worst-Case Boundaries, calculate the standard deviation of the lateral distribution of aircraft on final approach at the current range from the threshold. This standard deviation, computed from the RESALAB data found on page 3-7 of Reference 9, is then multiplied by 6.64 for the Single Criterion and by 3 for the Worst-Case Boundaries. For example (for the Single Criterion),

$$MAPWDn = 6.64 * (THMAPn * 0.0081676 + 33.576)$$

where:

MAPWDn = the distance from the MAP to point BnA
6.64   = the multiplier for the Single Criterion

For TERPS+3, this variable is computed from the definition of the TERPS final approach surface, found in paragraph 930 of Reference 4. The equation is:

$$MAPWDn = 500.0 + 0.15 * (THMAPn - 200.0)$$

The coordinates of the critical points on each boundary (shown in Figure A-2) are then calculated. (The center of this coordinate system is the threshold of runway 1. The x-axis is coincident with runway 1.) The first of these is point B1A, the starting point of the boundary 1 (that is, the point on the boundary opposite the MAP):

XB1A   = -THMAP1
YB1A   = MAPWD1

For the TERPS+3 analysis, the coordinates of the MAPs are then calculated so that the distance between them can be checked for the required 3-nmi separation:

XMAP1   = -THMAP1
YMAP1   = 0
XMAP2   = X2TH - THMAP2 * COSTH
YMAP2   = Y2TH + THMAP2 * SINTH

The next point to be calculated is point B1B, the point at which the straight segment of boundary 1 intersects the curved

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segment. It is important to note that, since the Worst-Case Boundary and the Single Criterion boundary are shaped differently than the TERPS+3 boundary, a different calculation is required. (The difference is that the radius of the curved segment is perpendicular to the boundary at point BnB in the first two cases, and perpendicular to the straight segment of the nominal flight path in the third case.) For the first two cases, then, the equations are:

$$XB1B = XB1A + SS1 * COS(ALPHA)$$
$$YB1B = YB1A + SS1 * SIN(ALPHA)$$

where:

SS1 = the length of the straight segment of boundary 1

ALPHA = the divergence angle of the straight segment of the boundary from the nominal flight path

For TERPS+3, there is no divergence angle since the distance from the nominal flight path to the boundary at point BnB is a constant (defined by TERPS). It should also be noted that the variable SS1 is the length of the straight segment of the nominal flightpath for TERPS+3. The calculations are:

$$XB1B = XMAP1 + SS1$$
$$YB1B = BWIDTH$$

where:

SS1 = the length of the straight segment of the nominal flight path for runway 1

BWIDTH = the distance from the nominal flight path to boundary at point BnB

The same points are then calculated for runway 2. Point B2A is calculated using the same formula for all criteria:

$$XB2A = X2TH - THMAP2 * COSTH - MAPWD2 * SINTH$$
$$YB2A = Y2TH + THMAP2 * SINTH - MAPWD2 * COSTH$$

Point B2B, however, requires separate formula. For the first two criteria,

$$XB2B = XB2A + SS2 * COS(THETA + ALPHA)$$
$$YB2B = YB2A - SS2 * SIN(THETA + ALPHA)$$

where:

SS2 = the length of the straight segment of boundary 2

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For TERPS+3:

$$XB2B = XMAP2 + SS2 * COSTH - BWIDTH * SINTH$$
$$YB2B = YMAP2 - SS2 * SINTH - BWIDTH * COSTH$$

where:

SS2 = the length of the straight segment of the nominal flight path for runway 2

The calculation of points BnA and BnB on each boundary enable the production of the equations for the straight segments of the boundaries. For line equations of the form $y = mx + b$,

$$XM1 = (YB1A - YB1B) / (XB1A - XB1B)$$
$$B1 = YB1A - XM1 * XB1A$$
$$XM2 = (YB2A - YB2B) / (XB2A - XB2B)$$
$$B2 = YB2A - XM2 * XB2A$$

where:

XMn = the slope of the line formed by the straight segment of boundary n

Bn = the y-intercept of the line described above.

Now the coordinates of the intersection of the straight segments of the boundaries are calculated. Note that the boundaries themselves may not actually intersect, but that the extensions of the two straight boundaries always intersect.

$$XBINT = (B2 - B1) / (XM1 - XM2)$$
$$YBINT = XM1 * XBINT + B1$$

Finally, the distance from the beginning of each boundary (opposite the MAP) to the intersection of the straight segments of the boundaries is calculated:

$$Dn = SQRT((XBINT - XBnA)**2 + (YBINT - YBnA)**2)$$

A.3.2.4 Subroutine Switch

This routine interchanges the coordinates between runways 1 and 2, if required. This is done for the case where the minimum separation falls between a straight boundary and the opposite arc so that the minimum separation will always be between the shorter of the two straight boundaries (measured from point

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"BnB" to the intersection) and the opposite arc. In other words, this check ensures that the minimum separation, if between a line and an arc, will always be between line 1 and arc 2.

The values interchanged (if this is necessary) are the length of the straight segments, SS1 and SS2; the distance from the beginning of each boundary to the intersection, D1 and D2; and the radii of the turning segment of each boundary, RAD1 and RAD2.

Following this interchange of coordinates, the coordinate system is translated and, in the case of the Single Criterion and the Worst-Case Boundaries, rotated slightly. The origin of the coordinate system is shifted to the center of arc 1, and the y-axis is rotated so that it is coincident with the radial from the origin to point "BnB." This step also simplifies the analysis in Minsep significantly for those two criteria. To avoid confusion between the two sets of coordinate systems, the coordinates of these points are renamed: XB1A becomes X1A, XBINT becomes XINT, XB2B becomes X2B, and so on.

It should be noted that the slightly different shape of the TERPS+3 boundary affects the analysis from this point on in the program. For the Single Criterion and the Worst-Case Boundaries, the radial from the center of either arc to point "B" is perpendicular to the straight boundary. (It will be seen later on that this greatly simplifies the minimum separation calculation.) However, for the TERPS+3 criterion, this radial is perpendicular to the nominal flight path. In effect, there is little advantage to translating the coordinate system for the TERPS+3 analysis, but the translation is retained for the sake of consistency within the program.

A.3.2.5 Subroutine Trap

This routine "traps" all cases where the boundaries intersect and, in the TERPS+3 case, where the MAPs are less than 3 nmi apart. The possibilities are two intersecting lines, two intersecting arcs, or the intersection of a line and an arc.

The first case to be evaluated is the possibility of two intersecting lines. If THETA, the angle between the runways, is equal to 90 degrees and if the following condition exists (illustrated in Figure A-3a), then the straight-line segments intersect:

Y2B .LE. Y1B and Y2A .GE. Y1A

Figure A-3a

Figure A-3b
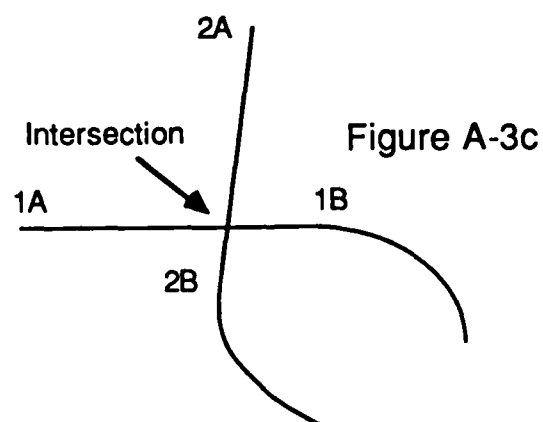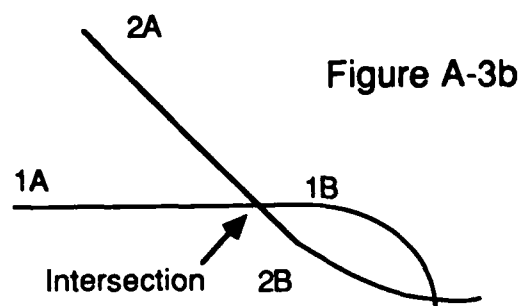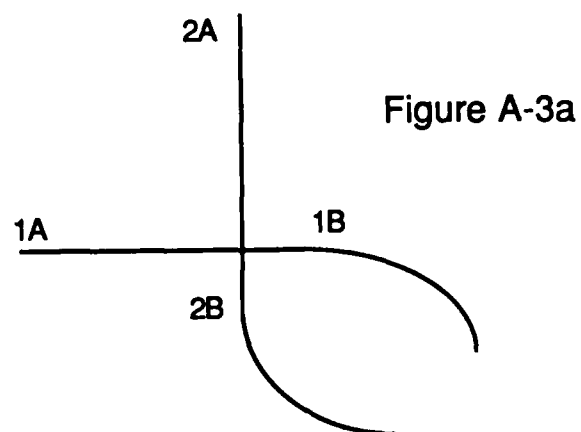
Figure A-3c

FIGURE A-3
INTERSECTING STRAIGHT BOUNDARY CASES

If the angle THETA is not equal to 90 degrees and XINT is less than X1B, then one of the following two conditions (illustrated in Figures A-3b and A-3c, respectively) must exist for the straight-line segments to intersect:

    XINT .LE. X2B and XINT .GE. X2A
    XINT .GE. X2B and XINT .LE. X2A

The second case to be evaluated is that of two intersecting arcs. If the distance from the centers of the two arcs is less than the sum of the radii, the two arcs intersect. That is, the two arcs intersect if the following is true:

    SQRT((X1C-X2C)**2 + (Y1C-Y2C)**2) .LE. (RAD1 + RAD2)

The third case is the intersection of an arc and a line. Only one case need be evaluated since Subroutine Switch made certain that the center of arc two will always be closer to line 1 than vice versa. The intersection of an arc and a line can be described by a quadratic equation.

If the discriminant of that quadratic equation is less than zero, then the equation has no real roots and the arc and line do not intersect. (See section A.4 for the proof of this assertion.) The discriminant is defined as:

    DISCRM = RAD2**2 - (RAD1-Y2C)**2

If the discriminant is greater than zero, then the smaller of the two roots of the equation is calculated:

    ROOT1 = X2C - SQRT(DISCRM)

If this root is less than or equal to X1B then the arc and line intersect.

The final case evaluated is the check for the required 3-nmi separation between MAPs for the TERPS+3 Criterion. This is accomplished by calculating the distance between MAPs, using the coordinates computed earlier in Subroutine Coords, and comparing it to 3 nmi.

If any of the cases described above are true, the INTRSC flag is set to true so that the main program does not call Minsep, but instead goes straight to the convergence algorithm logic.

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A.3.2.6 Subroutine Minsep

This routine calculates the minimum separation between the boundaries. (See Figure A-2.)

For the Single Criterion and Worst-Case Boundaries analyses (if they include the extended straight boundary), the calculation is a simple one because the minimum separation is always between line 1 and arc 2; the separation is simply the y-coordinate of the center of arc 2 minus the radius of arc 2 minus the y-coordinate of point B on boundary 1:

$$SEP = Y2C - RAD2 - Y1B$$

Since all of these values represent line segments parallel to the y-axis, they can be subtracted. (This simplification is a result of the translation and rotation of the coordinate system.) Note that, due to the extended straight boundary, this is the only possible case for the Single Criterion and Worst-Case Boundaries.

If the Worst-Case Boundaries or Single Criterion are evaluated without the extended straight boundary, it is possible that the minimum separation might occur between the two arcs. This separation is calculated with the following:

$$SEP = SQRT(X2C**2 + Y2C**2) - RAD1 - RAD2$$

Due to the slightly different shape of the TERPS+3 boundary, one of two somewhat more complicated cases must be evaluated. The first of the cases is the occurrence of the minimum separation between line 1 and arc 2. In this case, the point F on line 1 must be computed. First, the slope of line 1 must be calculated:

$$SLOPE = (Y1B - Y1A) / (X1B - X1A)$$

Next, solve for the y-intercept of line 1:

$$B1 = Y1A - SLOPE * X1A$$

Now solve for the y-intercept of the line perpendicular to line 1 that runs through the center of arc 2. This is possible because the coordinates of a point on the line (the center of arc 2) and the slope (the negative reciprocal of the slope of line 1) are known:

$$B4 = Y2C + (1. / SLOPE) * X2C$$

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Next, solve for point F:

    X1F = (B4 - B1) / (SLOPE + 1./SLOPE)
    Y1F = SLOPE * X1F + B1

Now that the coordinates of point F are computed, the distance between the center of arc 2 and point F can be found. The radius of arc 2 is then subtracted to arrive at the minimum separation:

    SEP = SQRT((X2C - X1F)**2 + (Y2C - Y1F)**2) - RAD2

In the second case, the minimum separation occurs between the two arcs. This case is evaluated in exactly the same manner as the same case for either Worst-Case Boundaries or Single Criterion.

A.4 Proof of the Third Case in Subroutine Trap

The third case evaluated in Subroutine Trap is the possibility of the intersection of arc 2 and line 1. (The case of the intersection of arc 1 and line 2 has been eliminated by Subroutine Switch.)

A circle with its center at the origin can be described by an equation of the following form:

    X**2 + Y**2 - R**2 = 0

where:

    X,Y = coordinates of any point on the circle
    R = the radius of the circle

Assume that the origin is at the center of arc 2. Any point on the circle that includes arc 2 can be described with:

    X**2 + Y**2 - RAD2**2 = 0

Any line can be described with an equation of the form y = mx + b, where m is the slope and b the y-intercept. Since the slope of line 1 is zero (that is, it is horizontal, as shown in Figure 3-1), it can be described by:

    Y = B

However, the y-intercept of this line, because the origin is assumed to be at the center of arc 2, is -(Y2C - RAD1) or (RAD1 - Y2C). To describe the point(s) on the intersection of this circle and line, the two equations are combined:

$$X**2 + (RAD1 - Y2C)**2 - RAD2**2 = 0$$

The solution of this quadratic equation will yield the intersection point(s) of the circle containing arc 2 and the line.

The general form of a quadratic equation is

$$A*X**2 + B*X + C = 0$$

where the solution is:

$$X = -B +/- SQRT(B**2 - 4*A*C) * (1/(2*A))$$

where A, B, and C are constants (B**2 - 4*A*c) is called the discriminant.

For the equation describing the intersection,

```
A = 1
B = 0
C = (RAD1 - Y2C)**2 - RAD2**2
```

The equation, in quadratic form, becomes:

$$X = +/- 0.5 * SQRT(- 4 * ((RAD1 - Y2C)**2 - RAD2**2))$$

or

$$X = +/- SQRT(RAD2**2 - (RAD1 - Y2C)**2)$$

To determine if the line and the circle intersect, it is necessary only to evaluate the discriminant. If there are no real roots to this equation (that is, if the discriminant is less than zero) then they do not intersect. If the discriminant is positive, then the value of the discriminant determines if arc 2 (as opposed to some other part of the circle) and line 1 intersect.

APPENDIX B

FORTRAN CODE

```
C Program Converge

C This program calculates the minimum decision height (DH)
C required for operating independent IFR approaches to
C converging runways.  One of three criteria may be used to
C determine this DH.  (Two of these criteria, Single Criterion
C and Worst-Case Boundaries, include an extended straight
C boundary by default.  This may be deleted if desired.)

C The program assumes a DH of 600 feet initially and then
C computes the minimum separation between boundaries.  This separation
C is then compared to the minimum required by that criterion.
C If they are not equal, the DH is revised and the process repeated.

C For further information, see the MITRE MTR "A Proposed Single
C Criterion for IFR Approaches to Converging Runways"

      PROGRAM CVG

      INTEGER ANALYS
      LOGICAL*2 DEBUG, INTRSC, INPFST, STBDRY
      CHARACTER*1 ANSWER
      REAL LOLMT, LOW, MAPWD1, MAPWD2

      COMMON /GNL/ DEBUG, DH, ANALYS, TANGS1, TANGS2, STBDRY, ANSWER
      COMMON /INP/ X1DEND,X2TH,Y2TH,X2DEND,Y2DEND,XINT,YINT,RWY1,
     &             RWY2,THETA,THETAP,COSTH,SINTH,COSTHP,SINTHP
      COMMON /PHY/ MAPWD1, MAPWD2, SS1, SS2, ALPHA, RAD1, RAD2
      COMMON /COO/ XB1A, YB1A, XB1B, YB1B, XB1C, YB1C, XB2A, YB2A,
     &             XB2B, YB2D, XB2C, YB2C, XBINT, YBINT, D1, D2,
     &             THMAP1, THMAP2
      COMMON /TPS/ XMAP1, YMAP1, XMAP2, YMAP2, BWIDTH

      PARAMETER (HIGH = 1000.0, LOW = 200.0, SEPMIN = 500.0)
      PARAMETER (GSLOP1 = 3.0, GSLOP2 = 3.0)

C Define the analysis-specific parameters (width at MAP,
C angle of divergence, length of each straight segment,
C and radius of each turn).

 PARAMETER (ALPHW = 2.50, SSW = 9114.0, RADW = 10633.0)
 PARAMETER (ALPHS = 7.53, SSS = 9114.0, RADS = 10633.0)
 PARAMETER (SST = 9114.0, RADT = 21266.0)
```

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```fortran
C There is no ALPHA (divergence angle) for TERPS since the
C wide end of the half-trapezoid (BWIDTH) is a constant 3038 feet.

C Initialize variables

      BWIDTH = 3038.0
      INPFST = .TRUE.
      DEBUG = .FALSE.
      TANGS1 = TAN(GSLOP1 / 57.29578)

      TANGS2 = TAN(GSLOP2 / 57.29578)

C Debug output desired?

      WRITE (*,*)
      WRITE (*, '(A\)') ' Do you want debug output? '
      READ (*,'(A1)') ANSWER
      WRITE (*,*)
      IF (ANSWER .EQ. 'Y' .OR. ANSWER .EQ. 'y') DEBUG = .TRUE.

C Select type of analysis desired

   10 WRITE (*, '(A)')
     & ' Select the type of analysis desired (1, 2, or 3):'
      WRITE (*, '(A)') ' 1.  Single Criterion'
      WRITE (*, '(A)') ' 2.  Worst-Case Boundaries'
      WRITE (*, '(A\)')
     & ' 3.  TERPS+3
      READ (*,*) ANALYS
      IF (ANALYS .LT. 1 .OR. ANALYS .GT. 3) GO TO 10
      WRITE (*,*)

C Verify that the extended straight boundary is desired
C for Single Criterion and Worst-Case Boundaries analyses.

      IF (ANALYS .NE. 3) THEN
        WRITE (*, '(A\)') ' Keep the extended straight boundary? '
        READ (*,'(A1)') ANSWER
        WRITE (*,*)
        IF (ANSWER .EQ. 'N' .OR. ANSWER .EQ. 'n') THEN
          STBDRY = .FALSE.
        ELSE
          STBDRY = .TRUE.
        ENDIF
      ENDIF
```

```fortran
C Let the user know what he's getting...

      IF (ANALYS .NE. 3) THEN
        IF (ANALYS .EQ. 1) THEN
          WRITE (*, '(A)') ' -- Single Criterion Analysis --'
        ELSE
          WRITE (*, '(A)') ' -- Worst-Case Boundaries Analysis --'
        ENDIF
        IF (STBDRY) THEN
          WRITE (*, '(A)') '    (Extended straight boundary)'
        ELSE
          WRITE (*, '(A)') '    (No extended straight boundary)'
        ENDIF
      ELSE
        WRITE (*, '(A)') ' -- TERPS+3 Analysis --'
      ENDIF
      WRITE (*,*)

C Initialize variables

      INTRSC = .FALSE.
      LOLMT = LOW
      HILMT = HIGH
      DH = (HIGH + LOW) / 2.0

C Define analysis-specific parameters

      IF (ANALYS .EQ. 1) THEN
        ALPHA = ALPHS / 57.29578
        SS1 = SSS
        SS2 = SSS
        RAD1 = RADS
        RAD2 = RADS
      ELSE IF (ANALYS .EQ. 2) THEN
        ALPHA = ALPHW / 57.29578
        SS1 = SSW
        SS2 = SSW
        RAD1 = RADW
        RAD2 = RADW
      ELSE
        SS1 = SST
        SS2 = SST
C Note:  for TERPS+3, SS1 and SS2 are the length of the straight
C segment as measured along the nominal flight path, not the
C boundary (as in the other two criteria).
        RAD1 = RADT
        RAD2 = RADT
      ENDIF
```

```fortran
C Get inputs from user

      CALL INPUT (INPFST)

C Calculate theta' -- the included angle between boundaries

      THETAP = THETA + 2 * ALPHA
      COSTHP = COS(THETAP)
      SINTHP = SIN(THETAP)

C Calculate coordinates of important points

   50 CALL COORDS

C Switch to a simpler set of coordinates and interchange the
C runways if necessary.

      CALL SWITCH

C Check for intersecting boundaries; if true, increase DH

      CALL TRAP (INTRSC)

C Calculate the minimum separation

      IF (.NOT. INTRSC) CALL MINSEP (SEP)

C Check for the proper separation and adjust the decision height.
C Note safety valves if the decision height converges on the
C the high and low limits.

C First case: Single Criterion or wcb; 500 feet required.

      IF (ANALYS .NE. 3) THEN
        IF (INTRSC .OR. SEP .LT. (SEPMIN - 2.0)) THEN
          LOLMT = DH
          DH = (DH + HILMT) / 2.0
          IF (DH .GT. (HIGH - 1.0)) GO TO 100
          GO TO 50
        ENDIF
        IF (SEP .GT. (SEPMIN + 2.0)) THEN
          HILMT = DH
          DH = (DH + LOLMT) / 2.0
          IF (DH .LT. (LOW + 1.0)) GO TO 110
          GO TO 50
        ENDIF
      ELSE
```

```fortran
C Second case: TERPS+3; no separation required.

      IF (INTRSC) THEN
        LOLMT = DH
        OLDDH = DH
        DH = (DH + HILMT) / 2.0
        IF (DH .GT. (HIGH - 1.0)) GO TO 100
        IF( ABS(OLDDH - DH) .GT. 0.1) GO TO 50
      ENDIF
      IF (SEP .GT. 4.0) THEN
        HILMT = DH
        OLDDH = DH
        DH = (DH + LOLMT) / 2.0
        IF (DH .LT. (LOW + 1.0)) GO TO 110
        IF( ABS(OLDDH - DH) .GT. 0.1) GO TO 50
      ENDIF
      ENDIF

C The decision height has been found.

      WRITE (*,'(A,F5.1,A)')' The decision height is ',DH,' feet.'
      GO TO 120

C Bail out:  the decision height is too low or too high.

  100 WRITE (*,*)
      WRITE (*,'(A)')' The decision height is 1000 feet or above.'
      GO TO 120
  110 WRITE (*,*)
      WRITE (*,'(A)')' The decision height is 200 feet or below.'

C Check for further analysis.

  120 WRITE (*,*)
      WRITE (*,'(A\)')' Do another case? '
      READ (*,'(A1)') ANSWER
      WRITE (*,*)
      IF (ANSWER .EQ. 'Y' .OR. ANSWER .EQ. 'y') GO TO 10

C All done...

 1000 END

C ------------------------------------------------------------------
C Subroutine Input
C Last edited 12/31/85
```

```
C This routine accepts the runway geometry inputs from the user
C and converts them to the proper units.

      SUBROUTINE INPUT (INPFST)

      LOGICAL*2 DEBUG, INPFST, STBDRY
      CHARACTER*1 ANSWER
      INTEGER ANALYS

      COMMON /GNL/ DEBUG, DH, ANALYS, TANGS1, TANGS2, STBDRY, ANSWER
      COMMON /INP/ X1DEND,X2TH,Y2TH,X2DEND,Y2DEND,XINT,YINT,RWY1
     &             RWY2,THETA,THETAP,COSTH,SINTH,COSTHP,SINTHP

C Check to see if the user wants to keep the previously-entered geometry.

      IF (INPFST) THEN
        INPFST = .FALSE.
      ELSE
        WRITE (*,'(A\)')' Keep the current runway geometry? '
        READ (*,'(A1)') ANSWER
        WRITE (*,*)
        IF (ANSWER .EQ. 'Y' .OR. ANSWER .EQ. 'y') GO TO 1000
      ENDIF

C Get inputs.

      WRITE (*,'(A\)')' Enter the runway lengths in feet: '
      READ (*,*) RWY1, RWY2
      WRITE (*,*)
      WRITE (*,'(A\)')' Enter the included angle in degrees: '
      READ (*,*) THETA
      WRITE (*,*)
      WRITE (*,10)
   10 FORMAT(' Enter the distances (in feet) from the departure ',
     &        'end of runway 1 and'/' and from the departure end ',
     &        'of runway 2 to the intersection: ')
      READ (*,*) DEND1P, DEND2P
      WRITE (*,*)

C Convert to the correct units.

      THETA = THETA / 57.29578
      COSTH = COS (THETA)
      SINTH = SIN (THETA)
```

```
C Calculate the runway-end coordinates.

      X1DEND = RWY1
      X2TH = (RWY1 + DEND1P) - COSTH * (RWY2 + DEND2P)
      Y2TH = SINTH * (RWY2 + DEND2P)
      X2DEND = X2TH + COSTH * RWY2
      Y2DEND = Y2TH - SINTH * RWY2
      XINT = X1DEND + DEND1P

C Fill the user in on the coordinates (if he so desires).

      IF (DEBUG) THEN
        WRITE (*,20) X1DEND, X2TH, Y2TH, X2DEND, Y2DEND
   20   FORMAT (' Runway end coordinates:'/
     &          ' ------------------------'/
     &          ' Runway 1 threshold: (0,0)'/
     &          ' Runway 1 dep. end: (',F6.0,'0)'/
     &          ' Runway 2 threshold: (',F6.0,',',F6.0,')'/
     &          ' Runway 2 dep. end: (',F6.0,',',F6.0,')')
        WRITE(*,*)
      ENDIF

 1000 RETURN
      END


C ----------------------------------------------------------------
C Subroutine Coords
C Last edited 12/31/85

C This routine calculates the coordinates of the points critical
C to the analysis.  These points include:

C B1A, B2A -- beginning of boundary (even with the MAP)
C B1B, B2B -- point at which curved boundary begins
C  BINT    -- intersection of two straight boundaries

      SUBROUTINE COORDS

      LOGICAL*2 DEBUG, INPFST, STBDRY
      CHARACTER*1 ANSWER
      INTEGER ANALYS
      REAL MAPWD1, MAPWD2

      COMMON /GNL/ DEBUG, DH, ANALYS, TANGS1, TANGS2, STBDRY, ANSWER
      COMMON /INP/ X1DEND,X2TH,Y2TH,X2DEND,Y2DEND,XINT,YINT,RWY1,
     &             RWY2,THETA,THETAP,COSTH,SINTH,COSTHP,SINTHP
      COMMON /PHY/ MAPWD1, MAPWD2, SS1, SS2, ALPHA, RAD1, RAD2
      COMMON /COO/ XB1A, YB1A, XB1B, YB1B, XB1C, YB1C, XB2A, YB2A,
     &             XB2B, YB2B, XB2C, YB2C, XBINT, YBINT, D1, D2,
     &             THMAP1, THMAP2
```

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```
          COMMON /TPS/ XMAP1, YMAP1, XMAP2, YMAP2, BWIDTH

C First, print the current decision height (if desired)

      IF (DEBUG) THEN
        WRITE (*,*)
        WRITE (*,'(A,F5.1)')' The current decision height is ',DH
        WRITE (*,*)' Subroutine Coords:'
      ENDIF

C Calculate the threshold-to-MAP distance (divide by tan of the glide
C slope)

      THMAP1 = (DH - 50.) / TANGS1
      THMAP2 = (DH - 50.) / TANGS2

C Calculate the lateral distance from the MAP to the starting point
C of the boundary (point A).  For SinCrit and WCB, this consists of
C calculating the standard deviation of the lateral distribution of
C aircraft at a given range on final approach (from the RESALAB
C data) and multiplying by 6.64 or 3.0.  For TERPS+3, this is the
C width of the final approach course at a given range on final.

      IF (ANALYS .EQ. 1) THEN
        MAPWD1 =  6.64 * (THMAP1 * 0.0081676 + 33.576)
        MAPWD2 =  6.64 * (THMAP2 * 0.0081676 + 33.576)
      ELSE IF (ANALYS .EQ. 2) THEN
        MAPWD1 =  3.0 * (THMAP1 * 0.0081676 + 33.576)
        MAPWD2 =  3.0 * (THMAP2 * 0.0081676 + 33.576)
      ELSE
        MAPWD1 = 500.0 + 0.15 * (THMAP1 - 200.0)
        MAPWD2 = 500.0 + 0.15 * (THMAP2 - 200.0)
      ENDIF

      IF (DEBUG) WRITE(*,*)' MAPWD1 ',MAPWD1,' MAPWD2',MAPWD2

C Calculate point B1A

      XB1A = -THMAP1
      YB1A = MAPWD1

C Calculate the coords of the missed approach points (MAPs)
C for the check on the 3-nmi required separation between them.

      IF (ANALYS .EQ. 3) THEN
        XMAP1 = -THMAP1
        YMAP1 = 0.
        XMAP2 = X2TH - THMAP2 * COSTH
```

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```fortran
          YMAP2 = Y2TH + THMAP2 * SINTH
          IF (DEBUG) THEN
            WRITE (*,*)' XMAP1',XMAP1,' YMAP1',YMAP1
            WRITE (*,*)' XMAP2',XMAP2,' YMAP2',YMAP2
            WRITE (*,*)' SS1',SS1,' SS2',SS2
          ENDIF
        ENDIF

C Calculate point B1B (point B on both boundaries is calculated
C differently for TERPS+3 since the wide end of the half-trapezoid
C is a constant width, BWIDTH.)

        IF (ANALYS .NE. 3) THEN
          XB1B = XB1A + SS1 * COS(ALPHA)
          YB1B = YB1A + SS1 * SIN(ALPHA)
        ELSE
          XB1B = XMAP1 + SS1
          YB1B = BWIDTH
        ENDIF

C Calculate the same points for runway 2

        XB2A = X2TH - THMAP2 * COSTH - MAPWD2 * SINTH
        YB2A = Y2TH + THMAP2 * SINTH - MAPWD2 * COSTH

        IF (ANALYS .NE. 3) THEN
          XB2B = XB2A + SS2 * COS(THETA + ALPHA)
          YB2B = YB2A - SS2 * SIN(THETA + ALPHA)
        ELSE
          XB2B = XMAP2 + SS2 * COSTH - BWIDTH * SINTH
          YB2B = YMAP2 - SS2 * SINTH - BWIDTH * COSTH
        ENDIF

C Here are the equations (in the form y=mx+b) for the straight
C parts of boundaries 1 and 2.

        XM1 = (YB1A - YB1B) / (XB1A - XB1B)
        B1 = YB1A - XM1 * XB1A
        XM2 = (YB2A - YB2B) / (XB2A - XB2B)
        B2 = YB2A - XM2 * XB2A

C Solve for the coords of the intersection

        XBINT = (B2 - B1) / (XM1 - XM2)
        YBINT = XM1 * XBINT + B1
```

```
C Calculate the distances from the beginning of the boundary
C to the intersection point.

      D1 = SQRT((XBINT - XB1A)**2 + (YBINT - YB1A)**2)
      D2 = SQRT((XBINT - XB2A)**2 + (YBINT - YB2A)**2)

C Print some serious debugging information

      IF (DEBUG) THEN
        WRITE (*,*)' XB1A',XB1A,' YB1A',YB1A
        WRITE (*,*)' XB1B',XB1B,' YB1B',YB1B
        WRITE (*,*)' XB2A',XB2A,' YB2A',YB2A
        WRITE (*,*)' XB2B',XB2B,' YB2B',YB2B
        WRITE (*,*)' XBINT',XBINT,' YBINT',YBINT
        WRITE (*,*)' D1',D1,' D2',D2,
        WRITE (*,*)' THMAP1',THMAP1,' THMAP2',THMAP2

        WRITE (*,*)' THETA',THETA,' THETAP',THETAP
        WRITE (*,*)' ALPHA',ALPHA
      ENDIF

      RETURN
      END


C -------------------------------------------------------------------
C Subroutine Switch
C Last edited 12/31/85

C This routine switches runways 1 & 2, if necessary, so that the
C runway with the shortest distance to the intersection is runway
C 1.  This eliminates a case to be analyzed in Minsep.

C This routine also changes to a simpler coordinate system to simplify
C the analysis to be performed in Subroutine Minsep.  It shifts the
C center of the coordinate system to the center of the turning arc
C of boundary 1.  In addition, things are rotated slightly, so that the
C straight segment of boundary 1 is parallel to the x-axis.  Note
C that only the items needed in Minsep are changed.

C It should also be noted that, since the TERPS surfaces are shaped
C a little differently, a different set of equations is necessary
C to define their coordinates.

      SUBROUTINE SWITCH

      LOGICAL*2 DEBUG, STBDRY
      CHARACTER*1 ANSWER
      INTEGER ANALYS
      REAL MAPWD1, MAPWD2
```

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```fortran
      COMMON /GNL/ DEBUG, DH, ANALYS, TANGS1, TANGS2, STBDRY, ANSWER
      COMMON /INP/ X1DEND,X2TH,Y2TH,X2DEND,Y2DEND,XINT,YINT,RWY1,
     &             RWY2,THETA,THETAP,COSTH,SINTH,COSTHP,SINTHP
      COMMON /PHY/ MAPWD1, MAPWD2, SS1, SS2, ALPHA, RAD1, RAD2
      COMMON /COO/ XB1A, YB1A, XB1B, YB1B, XB1C, YB1C, XB2A, YB2A,
     &             XB2B, YB2B, XB2C, YB2C, XBINT, YBINT, D1, D2,
     &             THMAP1, THMAP2
      COMMON /SWI/ X1A, Y1A, X1B, Y1B, X1C, Y1C,
     &             X2A, Y2A, X2B, Y2B, X2C, Y2C
      COMMON /TPS/ XMAP1, YMAP1, XMAP2, YMAP2, BWIDTH

C Check to see if the runways must be switched

      IF (DEBUG) WRITE (*,*)' Subroutine Switch:'
      IF ((D1 - SS1) .LT. (D2 - SS2)) THEN

C Reverse the pertinant runway coordinates

         TEMP = SS1
         SS1 = SS2
         SS2 = TEMP
         TEMP = D1

         D1 = D2
         D2 = TEMP
         TEMP = RAD1
         RAD1 = RAD2
         RAD2 = TEMP
         IF (DEBUG) WRITE(*,*)' Reverse runway coordinates.'
      ENDIF

C Shift to the new coordinate system

      IF (ANALYS .NE. 3) THEN
        X1A = -SS1
        Y1A = RAD1
        X1B = 0.
        Y1B = RAD1
        X1C = 0.
        Y1C = 0.

        XINT = D1 - SS1
        YINT = RAD1

        X2A = XINT - D2 * COSTHP
        Y2A = YINT + D2 * SINTHP
        X2B = X2A + SS2 * COSTHP
        Y2B = Y2A - SS2 * SINTHP
        X2C = X2B + RAD2 * SINTHP
        Y2C = Y2B + RAD2 * COSTHP
```

B-11

```fortran
      ELSE
        XSHIFT = THMAP1 - SS1
        YSHIFT = RAD1 - BWIDTH
        IF (DEBUG) WRITE(*,*)' XSHIFT',XSHIFT,' YSHIFT',YSHIFT
        X1A = XB1A + XSHIFT
        Y1A = YB1A + YSHIFT
        X1B = XB1B + XSHIFT
        Y1B = YB1B + YSHIFT
        X1C = 0.
        Y1C = 0.

        XINT = XBINT + XSHIFT
        YINT = YBINT + YSHIFT


        X2A = XB2A + XSHIFT
        Y2A = YB2A + YSHIFT
        X2B = XB2B + XSHIFT
        Y2B = YB2B + YSHIFT
        X2C = X2B + RAD2 * SINTH
        Y2C = Y2B + RAD2 * COSTH
      ENDIF

C Print some serious debugging information

      IF (DEBUG) THEN
        WRITE (*,*)' X1A',X1A,' Y1A',Y1A
        WRITE (*,*)' X1B',X1B,' Y1B',Y1B
        WRITE (*,*)' X2A',X2A,' Y2A',Y2A

        WRITE (*,*)' X2B',X2B,' Y2B',Y2B
        WRITE (*,*)' X2C',X2C,' Y2C',Y2C
        WRITE (*,*)' XINT',XINT,' YINT',YINT
      ENDIF

      RETURN
      END


C --------------------------------------------------------------------

C Subroutine Trap
C Last edited 12/31/85

C This routine is designed to trap those cases where the boundaries
C intersect.

      SUBROUTINE TRAP (INTRSC)
```

```fortran
      LOGICAL*2 INTRSC, DEBUG, STBDRY
      CHARACTER*1 ANSWER
      INTEGER ANALYS
      REAL MAPWD1, MAPWD2

      COMMON /GNL/ DEBUG, DH, ANALYS, TANGS1, TANGS2, STBDRY, ANSWER
      COMMON /INP/ X1DEND,X2TH,Y2TH,X2DEND,Y2DEND,XINT,YINT,RWY1,
     &             RWY2,THETA,THETAP,COSTH,SINTH,COSTHP,SINTHP
      COMMON /PHY/ MAPWD1, MAPWD2, SS1, SS2, ALPHA, RAD1, RAD2
      COMMON /SWI/ X1A, Y1A, X1B, Y1B, X1C, Y1C,
     &             X2A, Y2A, X2B, Y2B, X2C, Y2C
      COMMON /TPS/ XMAP1, YMAP1, XMAP2, YMAP2, BWIDTH

      INTRSC = .FALSE.

C Case 1: two intersecting lines

      IF (ABS((THETAP * 57.29578) - 90.) .LE. 0.05) THEN
        IF (Y2B .LE. Y1B .AND. Y2A .GE. Y1A) GO TO 950
      ELSE
        IF (XINT .LE. X1B ) THEN
          IF (XINT .LE. X2B .AND. XINT .GE. X2A) GO TO 950
          IF (XINT .GE. X2B .AND. XINT .LE. X2A) GO TO 950
        ENDIF
      ENDIF

C Case 2: two intersecting arcs

      IF (SQRT((X1C-X2C)**2 + (Y1C-Y2C)**2) .LE.
     &    (RAD1 + RAD2)) GO TO 960

C Case 3: intersection of an arc and a line

      DISCRM = RAD2**2 - (RAD1-Y2C)**2
C If the discrim < 0 there are no real roots and they don't intersect.
      IF (DISCRM .GE. 0.0) THEN
        ROOT1 = X2C - SQRT(DISCRM)

C Don't need the positive root; it only intersects if the lines intersect.
        IF (ROOT1 .LE. X1B) GO TO 970
      ENDIF

C Case 4: check for the required 3-nmi separation between MAPs for TERPS+3

      IF (ANALYS .EQ. 3) THEN
        IF (SQRT((XMAP2 - XMAP1)**2 + (YMAP2 - YMAP1)**2)
     &      .LT. 18228.0) GO TO 980
      ENDIF
      GO TO 1000
```

B-13

```fortran
C Reset flag and print out results (if desired)

  950 IF (DEBUG) WRITE (*,*) ' The two lines intersect.'
      GO TO 990
  960 IF (DEBUG) WRITE (*,*) ' The two arcs intersect.'
      GO TO 990
  970 IF (DEBUG) WRITE (*,*) ' A line and an arc intersect.'
      GO TO 990
  980 IF (DEBUG) WRITE (*,*)' The MAPs are less than 3 nmi apart.'

  990 INTRSC = .TRUE.

 1000 RETURN
      END


C ------------------------------------------------------------------
C Subroutine Minsep
C Last edited 12/31/85

C This routine calculates the separation between boundaries.  If the
C extended straight boundary is present for SinCrit or WCB, the
C minimum separation for these criteria will always lie between
C line 1 and arc 2.  If it is not present (and for TERPS+3), it is
C also possible that the minimum separation will occur between
C the two arcs.

      SUBROUTINE MINSEP (SEP)

      LOGICAL*2 DEBUG, STBDRY
      CHARACTER*1 ANSWER
      INTEGER ANALYS
      REAL MAPWD1, MAPWD2

      COMMON /GNL/ DEBUG, DH, ANALYS, TANGS1, TANGS2, STBDRY, ANSWER
      COMMON /INP/ X1DEND,X2TH,Y2TH,X2DEND,Y2DEND,XINT,YINT,RWY1,
     &             RWY2,THETA,THETAP,COSTH,SINTH,COSTHP,SINTHP
      COMMON /PHY/ MAPWD1, MAPWD2, SS1, SS2, ALPHA, RAD1, RAD2
      COMMON /SWI/ X1A, Y1A, X1B, Y1B, X1C, Y1C,
     &             X2A, Y2A, X2B, Y2B, X2C, Y2C

      IF (ANALYS .NE. 3) THEN
       IF (STBDRY .OR. X2C .LE. 0) THEN
```

```
C Case 1: minimum separation occurs between line 1 and arc 2

          SEP = Y2C - RAD2 - Y1B
          IF (DEBUG) THEN
            X1F = X2C
            Y1F = Y1B
            X2F = X2C
            Y2F = Y2C - RAD2
            WRITE(*,*) 'The min. sep. is between line 1 and arc 2:'
          ENDIF
        ELSE

C Case 2: minimum separation occurs between the two arcs

          SEP = SQRT(X2C**2 + Y2C**2) - RAD1 - RAD2
          IF (DEBUG) THEN
            A = Y2C / X2C
            B = 1.0 + A**2
            X1F = RAD1 / SQRT(B)
            Y1F = A * X1F
            X2F = X2C - SQRT(RAD2**2 / B)
            Y2F = A * X2F
            WRITE(*,*) 'The min. sep. is between the two arcs:'
          ENDIF
        ENDIF
      ELSE

C TERPS+3 analysis

        IF (X2C .LE. 0.) THEN

C Case 1: minimum separation occurs between line 1 and arc 2.
C For this case, point 1F on line 1 must be found.

          SLOPE = (Y1B - Y1A) / (X1B - X1A)
C line 1: solve for y-intercept
          B1 = Y1A - SLOPE * X1A
C solve for the y-intercept of the line perpendicular to line 1 that
C runs through the center of arc 2 (call it line 4).
          B4 = Y2C + (1. / SLOPE) * X2C
C solve for point 1F
          X1F = (B4 - B1) / (SLOPE + 1./SLOPE)
          Y1F = SLOPE * X1F + B1
C now, get the separation
          SEP = SQRT((X2C - X1F)**2 + (Y2C - Y1F)**2) - RAD2
          IF (DEBUG) THEN
            WRITE(*,*) 'The min. sep. is between line 1 and arc 2:'
          ENDIF
```

```fortran
C Case 2: minimum separation occurs between the two arcs

      ELSE
        SEP = SQRT(X2C**2 + Y2C**2) - RAD1 - RAD2
        IF (DEBUG) THEN
          A = Y2C / X2C

          B = 1.0 + A**2
          X1F = RAD1 / SQRT(B)
          Y1F = A * X1F
          X2F = X2C - SQRT(RAD2**2 / B)
          Y2F = A * X2F
          WRITE(*,*) 'The min. sep. is between the two arcs:'
        ENDIF
      ENDIF
   ENDIF

   IF (DEBUG) THEN
     WRITE(*,*)' X1F', X1F,' Y1F', Y1F
     WRITE(*,*)' X2F', X2F,' Y2F', Y2F
     WRITE(*,*)' The current separation is ',SEP
   ENDIF

   RETURN
   END
```

APPENDIX C

ACRONYMS

AGL	Above Ground Level
ALP	Airport Layout Plan
AOCI	Airport Operators Council International
CAT	Category
CRM	Collision Risk Model
DH	Decision Height
DOS	Disk Operating System
FAA	Federal Aviation Administration
ft	feet
FORTRAN	Formula Translator Language
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meterological Conditions
m	Meters
MAP	Missed Approach Point
MLS	Microwave Landing System
NAVAID	Navigational Aid
nmi	nautical miles
TERPS	Terminal Instrument Procedures
VFR	Visual Flight Rules

APPENDIX D

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END

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